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CHEMICAL AND PETROCHEMICAL SECTOR

Potential of best practice technology and other measures for improving energy efficiency

IEA INFORMATION PAPER

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Acknowledgements

The authors would like to thank Giuseppe Astarita (ICCA), Kees den Blanken (COGEN Nederland), Pieter Boot (ECN & CIEP), Maurits Clement (SenterNovem), Michel Francoeur (IEA), Ed Gartner (SRI), Russell Heinen (SRI), Tom Kerr (IEA), Hans Keuken (PDC), Nobuaki Mita (JPCA), Shigeru Moriyama (Japan Soda Association), Ben Muirheid (IFA), Shuichi Nakai (Tosoh corporation), Hi-Chun Park (Inha University), Robert Powell (IEA), Michel Prud'Homme (IFA), Frank Roberto (ExxonMobil), Arseen Seys (EuroChlor), Vianney Schyns (SABIC), Lieven Stalmans (Borealis), Peter Steenbergen (COGEN Nederland), Kevin T. Swift (ACC), Peter Taylor (IEA), Nathalie Trudeau (IEA), Michael P. Walls (ACC), Wolfgang Weber (BASF), Andrea Weigel (CEFIC) and Keith C. Wilson (PotashCorp) for their valuable comments.

This work was financially supported by the Dutch government.

Note: This Information Paper complements the book chapter "Chemical and petrochemical sector" in IEA's new publication *Energy Technology Transitions for Industry: Strategies for the Next Industrial Revolution*.

Executive summary

With a share of more than 30% of the total industrial energy use worldwide (including feedstocks), the chemical and petrochemical sector is by far the largest energy user in industry. The sector is faced with the challenge of saving energy primarily for economic and environmental reasons. This information paper assesses the energy saving potential and CO_2 emission reductions related to the application of Best Practice Technology (BPT) in chemical processes. In addition, the energy saving potentials of combined heat and power (CHP) and recycling and energy recovery are estimated. The analyses were performed for selected countries and for the world as a whole for the year 2006.

Energy and CO_2 indicators for the chemical and petrochemical sector

The energy efficiency index and improvement potentials were estimated by applying a *top-down* calculation method for 57 processes leading to 66 chemicals. In this *top-down* approach, the energy saving potential was estimated by comparing the chemical and petrochemical sector's current energy use according to IEA energy statistics with the BPT energy use for the 57 processes; in order to account for all other processes the total energy use for the 57 processes was scaled with a uniform coverage value of 95% (for all countries). The results show that the energy saving potentials in the short to medium term are around 5-15% for the world as a whole and for Brazil, Canada, France, Italy, Japan, and Taiwan. For some countries, the energy efficiency improvement potentials are negative, indicating that the existing processes are more efficient than BPT. Possible methodological and data-related reasons are discussed in the text of this paper. Given the variability of the results, the uncertainty range is estimated at ±10 percentage points, but it may be larger for some countries (*e.g.* USA).

In addition to the *top-down* approach a *bottom-up* approach was applied (discussed in Appendix B). This *bottom-up* approach is based on estimated average specific energy consumption values for current production processes. Multiplication of these specific energy consumption values with production data leads to calculated energy requirements which can be compared to the energy requirements reported in statistics, resulting in actual energy coverage values. It was found that these partly differ from the uniformly applied value of 95% as applied in *top-down* approach, hence pointing to another source of uncertainty.

Given the uncertainties the *top-down* approach is subject to, it cannot be directly applied for target setting, but can provide a useful indication of the energy savings potential in the sector. While the results show that there is urgent need to improve the quality and the availability of the input data, the approach provides reasonable approximations of energy efficiency values. The comparison of the results of the *top-down* analysis to other sectors shows that the energy saving potential in the chemical and petrochemical sector is smaller than many other energy intensive industries, which is explained by the high share of feedstock (non-energy use).

The bulk of the carbon and energy stored in synthetic organic chemicals is released in the use phase or in the waste stage (*e.g.*, waste incineration of polymers). Therefore, in addition to energy efficiency improvements, other approaches such as biomass feedstock use should be explored to reduce CO_2 emissions in the chemical and petrochemical sector. Other important options for saving energy are improvements in recycling and energy recovery and enhanced implementation of Combined Heat and Power (CHP, also referred to as cogeneration). For these options the size of the savings strongly depends on local circumstances. When calculating the savings for CHP, regional conditions determine the appropriate reference technology. In some regions it is appropriate to assume separate power production in a modern, highly efficient power plant; in others the average grid efficiency should be assumed. Depending on these circumstances primary energy savings by co-generation can be more than 20% (when compared to average grid efficiency) or only 4-10% (when compared to highly efficient power plants).

Findings: substantial energy and CO_2 savings possible, but better data and further work needed

Adding up the globally achievable primary energy savings *within* the chemical sector (by applying BPTs for process heat and electricity, and by energy and process integration) with savings that are enabled by the chemical and petrochemical sector but are occurring elsewhere (recycling & energy recovery and CHP) results in a total of 12.1 EJ per year. When compared to the energy use of the chemical and petrochemical sector as reported in energy statistics, this potential translates to approximately 35% savings. Similarly achievable CO_2 emission reductions are in the order of 20-35% based on unchanged current fuel use and feedstock mix.

The results indicate that progress must be made primarily on data availability and data quality. There is urgent need for global benchmark data, ideally for the approximately 50 to 100 most energy intensive chemicals. Only if such benchmark activities are initiated, will the data required for cross-country analyses become available. Stronger collaboration is required between energy experts in companies and energy statisticians in order to improve the quality and international consistency of production and energy statistics. Moreover, available statistics fail to provide insight into the breakdown of power use of the sector. A better understanding must be gained that would also allow dedicated analysis at the country level.

Furthermore, the methodology applied for estimating the energy efficiency index must be extended on a number of issues. As first steps, the energy saving potentials of CHP and energy integration on chemical sites by heat cascading should be incorporated into the methodology. The current methodology accounts for the energy efficiency improvement potentials in the core of the processes only. A broader methodology that covers the whole life cycle of chemical products needs to be developed that would allow for process energy efficiency potentials and other measures related to the sector. Such an approach can credit the production of chemicals from renewable feedstocks as well as include the efficiency gains from post-consumer waste treatment options of plastics, *i.e.* recycling and energy recovery.

In conclusion, there are important tasks ahead for authorities, institutes and the sector to raise the quality of energy and CO_2 data collection and methodology to a level comparable with other sectors, notably iron and steel and cement.

1. Introduction

This information paper was prepared as background document on the global chemical and petrochemical sector for the new IEA publication *Energy Technology Transitions in Industry* (IEA, 2009). It provides further, more detailed information on the methodology and data issues for energy efficiency indicators for the sector. The indicators discussed offer insight regarding the energy efficiency improvement potential in the short to medium term (by proven technologies). Energy efficiency potentials for the long term (including new technologies) are not discussed here but they are studied in the *Energy Technology Transitions in Industry* chapter (IEA, 2009).

Following the G8 "Plan of Action for Climate Change, Clean Energy and Sustainable Development" in Gleneagles in 2005, the iron and steel industry, the cement industry, and the aluminium industry have recognised the importance of energy and CO_2 indicators and are working on sectoral accounting frameworks and datasets that provide a workable solution in terms of the amount of work, data accessibility, competitiveness limitations, and accuracy. The chemical and petrochemical sector poses a special challenge because of the wide range of products. This has so far prevented the development of a widely used indicator methodology. However, the industry is now increasingly active in this area.

The chemical and petrochemical sector has a long tradition of energy analysis. The International Fertilizer Industry Association (IFA) publishes benchmarking results for the majority of the world ammonia plants. For steam crackers, Solomon Associates prepares benchmarking studies that cover about 50% of the world crackers. For other petrochemical products, other consultancies provide such services. The IEA publication *Tracking Industrial Energy Efficiency and CO_2 Emissions* (2007) provides an overview of these activities. While these initiatives are successfully conducted and have their merits, there are also several unresolved problems. First, the sum of these initiatives does not cover all energy use in this sector worldwide. Second, the benchmarking is not done on a country level and therefore such information, which would be a key input for climate policy, is not available for many countries. And third, many of these benchmarking studies are confidential and thus, it is unlikely that the data will ever become available. The IEA approach complements other approaches and its goal is to provide a methodology that overcomes these shortcomings.

While the sector produces thousands of products, not all have a high relevance from an energy and CO_2 perspective. The analysis presented in this paper was conducted for the 57 most important chemical and petrochemical processes (these processes produce the 66 largest chemicals in terms of physical production volumes). We explain the methodology and we discuss the results for thirteen countries and for the world as a whole. The comprehensive character and the reliance on publicly available data are major advantages of the proposed approach.

The analysis suggests that the energy saving potential in the chemical and petrochemical sector is smaller than in some of the other energy intensive industries, which can be attributed to the high share of feedstock (non-energy use). It is also evident that the methodology needs further refinement and should be complemented by benchmarking on a process level. Future improvements to this analysis should also include the impact of heat cascading in petrochemical complexes. The results of this information paper are not suited to rank countries or to set efficiency targets.

2. Energy efficiency improvement potentials and CO_2 emission reduction by Best Practice Technology (BPT) in chemical processes

In this chapter, we first introduce the methodology for establishing the potential for energy savings and CO_2 emissions reductions by Best Practice Technology (BPT). We then present our findings on energy efficiency improvement and CO_2 emission reduction potentials in the chemical and petrochemical industries of selected countries and the world as a whole (for the year 2006).

2.1. Methodology

2.1.1. Methodology for estimating energy efficiency improvement

The indicator analysis makes use of a *Top-down* approach in order to estimate the energy saving potential and CO_2 emission reductions by comparing the current performance of the sector to Best Practice Technology (BPT). To this end BPT energy use is compared with current energy use according to IEA energy statistics. The methodology is in line with the approach explained in the previous IEA publications (IEA, 2007; 2008a); however it uses a more recent and more extensive dataset.

In this information paper (and likewise in the publication *Energy Technology Transitions in Industry*, IEA, 2009) the choice has been made to determine the energy saving potentials using best *practice* technology (BPT) instead of best *available* techniques (BAT). BPT represents the most advanced technologies that are currently in use at industrial scale and they are therefore, by definition, economically viable. In contrast, *best available techniques* (BAT) are generally more advanced in terms of the technology level but their large-scale viability (including economic viability) is not always certain. In certain cases, both are identical.

The methodology for determining the energy efficiency improvement potentials in the chemical and petrochemical sector consists of the following steps: First the production volumes are multiplied by BPT values in order to determine the minimum achievable energy use associated with each process at the country level. In order to estimate BPT energy use at the sector level the BPT energy use of all 57 processes is added up and it is scaled by dividing by the average coverage value of 95% (a uniform value is used for all countries). By comparison of the resulting total with the total energy use of the chemical and petrochemical sector reported in the IEA energy statistics an energy efficiency index (EEI) is established, *i.e.* a measure of the extent to which current practice compares to potential best practice if BPTs were to be used throughout the sector.[1] Energy efficiency improvement potentials are estimated by subtracting EEI from 1 (= 1 – EEI).

The method is applied by simultaneously accounting for process energy and feedstock energy. An alternative approach would be to estimate the energy efficiency improvement potentials solely for process energy use. Such an approach would reflect more accurately the fact that no savings can be

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[1] The improvement potential determined in this analysis assumes that the whole industry switches to new plants according to best practice technology. Savings by revamping existing plants can be smaller.

made in the heating value of organic chemicals. However, process energy use and feedstock energy use cannot be reliably separated given the lack of consistency between countries in the definition of energy use and non-energy use (*i.e.*, feedstock use) as reported in energy statistics (Weiss *et al.*, 2008; see also Footnote 12). It is planned to conduct separate analyses of process energy usage only, but this will only be feasible if a major effort is made by all national statistics offices and industry associations to ensure consistent reporting of feedstock use.

The methodology described above refers exclusively to fuel use (including steam and feedstocks). For *electricity*, a simpler estimate for calculating energy efficiency improvement was applied. The reason is that the *bottom-up* energy analysis of the chemical and petrochemical industry showed that the *bottom-up* process data explain only one third of the total electricity use (see Table 15 in Appendix B). The remainder is probably used to run pumping equipment for pipelines and tanks and auxiliary uses which are outside the core process boundaries (not included in BPT values). The overall short to medium-term saving potential in electricity use in the sector has been estimated at 20% (see Box 1 and Table 2).

There are limitations concerning input data and also the method does not account for a number of issues that may affect the efficiency estimates:

- Regarding input data, some BPT data represent the situation in Europe rather than the world (because data for the world were not available);
- concerning the applied method, a particularly high level of energy integration on chemical sites by heat cascading which can reduce the energy use below BPT (this is not accounted for by the BPT values),[2] and
- the efficiency improvements by CHP were not considered.

A more elaborate method could be developed that accounts for these issues, but at this moment the availability of reliable data is a limiting factor.

2.1.2. CO_2 reduction potentials by best practice technology (BPT)

A CO_2 emission index has been developed that builds on the energy efficiency index. It covers only *direct* CO_2 emissions by application of Best Practice Technology (BPT). It excludes the sector's electricity use and the related emissions (indirect emission) and emissions in the use phase and the waste treatment stage. It also excludes non-CO_2 greenhouse gas emissions.

The *potential* direct CO_2 emissions are calculated by multiplying the current fossil fuel and feedstock use data reported in IEA energy statistics with fossil-fuel specific emission factors. The *real* emissions (*actual* emissions) are lower because the carbon stored in the petrochemical products is not released as a consequence of activities of the chemical and petrochemical sector (part of this carbon is released later on as a consequence of waste management activities). The carbon storage in polymers, resins, fibres and urea is calculated by multiplying their production volumes with their carbon content (see Table 4).[3] Then

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[2] By heat cascading we mean that if a process uses high-pressure steam, this may be re-usable as medium pressure steam and subsequently possibly also as low-pressure steam. However, in the analysis various pressure levels across process are not accounted for and we do not have insight into the extent of heat cascading applied in the chemical and petrochemical sector. As a note of caution, heat cascading should not be confused with crediting potential steam export from exothermic processes. We account for this separately in our BPT values (see Section 2.2).

[3] The identical set of polymers, resins and fiber types as shown in Table 1 are used for the calculation of carbon stored.

the carbon storage is deducted from the current *potential* CO_2 emissions for calculating the total current direct CO_2 emissions (*actual* emissions) of the chemical and petrochemical sector (see Table 5).[4]

The same methodology is applied once more using the values for BPT.[5] By comparison with the results for the current situation the reduction potentials for direct CO_2 emissions are calculated. Carbon storage in urea fertilizer is credited because IEA follows the methodology of the Intergovernmental Panel on Climate Change (IPCC) according to which emissions are accounted for in the sector where they occur. Therefore the CO_2 emissions from the decomposition of urea are taken into account in the agricultural sector.

Production volumes of those polymers and fibres that are shown in Table 1 are the most important ones in terms of quantity, however the product list is not complete and therefore does not cover *total* amount of carbon embedded in final products for long periods of time. In conclusion, this results in (some) underestimation of carbon stored in the chemicals and consequently (some) overestimation of the emissions. An alternative approach would be to estimate the carbon embedded in high value chemicals (HVC), methanol, urea and intermediate products (for which data are available). This approach does not account for the use of such intermediates for short-life end products where CO_2 is emitted in the use phase and in waste treatments stages (Patel *et al.*, 2005). Application of this approach leads to higher carbon storage and therefore to lower emissions. However some of the carbon in HVC, methanol and urea is released quickly if it is used for the production of short-lived products (*e.g.*, fertilizers); therefore this methodology suffers from overestimating the carbon storage. For this reason the approach of calculating carbon storage based on polymers has been chosen, but with a note of caution that the emissions may be somewhat overestimated.

2.2. Input data and basic assumptions

Three data sources were used, *i.e.*, (i) IEA energy statistics, (ii) specific energy consumption data for Best Practice Technology (BPT) and (iii) production data. The latter were provided by SRI Consulting (2008) for the purpose of this project.[6] This chapter discusses primarily the BPT data used.

Table 1 provides a comprehensive overview of the BPT values for the most important processes of the chemical and petrochemical sector (57 processes for 66 products).[7] While Table 1 also reports electricity use, the approach described above was applied only for fuels (including steam). In contrast, for electricity, the saving potential has been estimated at 20% (see Box 1, Table 2).

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[4] Worldwide about 100 Mt of CO_2 is used per year for urea production (2007) and this sequestered amount is released again in the agricultural sector.

[5] By analogy with the explanation given in Section 2.1 the production volumes are multiplied by BPT values, the resulting minimum achievable energy use is added up for all 57 processes, it is divided by the coverage value and finally multiplied with the CO_2 emission factors (by fuel type). Again carbon storage is deducted for calculating the total direct CO_2 emissions by application of BPT.

[6] Production data for all organic chemicals and polymers (except for polycarbonate) were provided by SRI (2008). The production volumes of most inorganics and of polycarbonate originate from Chemweek (2007a, b, c, d). Production volumes of other inorganics were taken from the US Geological Survey Minerals Yearbook (USGS, 2008a, b). The source of the ethanol production data is the Renewable Fuels Association (RFA, 2009) and the production volumes for urea were provided by the International Fertiliser Association (IFA, 2009a).

[7] Steam cracking and aromatics extraction are counted as one process each. Methanol from natural gas and coal are counted as two processes. By analogy ammonia production from natural gas, oil, and coal are counted as three processes. The product group “Urea Formaldehyde (UF) & Other resins & fibers” and the product group “Synthetic rubber & latex” are counted as one process each (see related footnotes in Table 1).

Table 1: BPT values on the specific energy consumption for the production of key chemicals (left: in final energy terms, denoted with index ”f”; right: in primary energy terms, denoted with index “p”)[1]

Process	In final energy terms (GJ_f/t)				In primary energy terms (GJ_p/t)				Sources
	Electricity	Feedstock	Fuel	Steam	Electricity	Feedstock	Fuel	Steam	
Organic									
Acetic acid	0.5			4.1	1.2			4.6	Meyers, 2005
Acetone	0.2			9.8	0.5			10.9	Chauvel and Lefebvre, 1989
Acrylonitrile (ACN)	0.8		0.3	-6.4	2.1		0.3	-7.1	Schyns, 2006
Adipic acid[2]	0.5		1.0	18.5	1.2		1.0	20.6	Chauvel and Lefebvre, 1989
Benzene (steam cracking)	0.3	0	13.1	-1.4	0.7	0	13.1	-1.5	Schyns, 2006
Benzene (aromatics extraction)	0.1	45		2.0	0.1	45		2.2	Schyns, 2006
Butadiene (steam cracking)	0.3	0	13.1	-1.4	0.7	0	13.1	-1.5	Schyns, 2006
Butadiene (C_4 separation)	0.5	45		6.7	1.3	45		7.5	Schyns, 2006
Butylene	0.1	45		2.0	0.1	45		2.2	Schyns, 2006
Caprolactam	1.1		0.2	-3. 2	2.6		0.2	-3.6	Schyns, 2006
Cumene			2.1	-2.8			2.1	-3.1	Meyers, 2005
Cyclohexane[2]	0.1			-1.6	0.2			-1.8	Industrial sources
Dimethyl terephthalate (DMT)[2]			4.7				4.7		Industrial sources
Diphenylmethane diisocyanate (MDI)[2]	3.2			0.9	8.0			1.0	Industrial sources
Ethanol[2, 3]	0.8			22.2	2.0			23.1	BREW Study, 2006
Ethylene[4]	0.3	45	13.1	-1.4	0.7	45	13.1	-1.5	Schyns, 2006
Ethylbenzene (EB)	0.1			3.3	0.2			3.6	Meyers, 2005
Ethylene dichloride (EDC)	0.2		4.4		0.6		4.4		IEA estimates
Ethylene glycol (EG)	0.2		0.8	3.5	0.5		0.8	3.9	Industrial sources

Ethylene oxide (EO)	0.8		2.5		2.0		2.5		Industrial sources
Formaldehyde[5]	0.8			-4.8	1.9			-5.3	IPTS/EC, 2003
Isopropyl alcohol (IPA)	0.1		5.2	5.4	0.2		5.2	6.0	Chauvel and Lefebvre, 1989
Maleic anhydride	0.1			2.0	0.3			2.2	IEA estimates
Melamine[5]	1.9		7.9	3.9	4.7		7.9	4.3	Schyns, 2006
Methacrylate	0.1			2.0	0.3			2.2	IEA Estimates
Methanol from natural gas[6]		20		8.5		20		9.4	IEA Estimates
Methanol from coal[6]		20		12.8		20		16.1	IEA Estimates
Methyl tert butyl ether (MTBE)	0.1			0.8	0.1			0.9	Schyns, 2006
Oxo-alcohols	2.5			2.3	1.0			2.1	Meyers, 2005
Phenol	0.6			9.1	1.5			10.1	Meyers, 2005
Phthalic anhydride	0.7		20		1.8		20		IEA Estimates
Propylene (steam cracking)	0.3	45	13.1	-1.4	0.7	45	13.1	-1.5	Schyns, 2006
Propylene (FCC)[7]	0.1	45		2.0	0.1	45		2.2	Schyns, 2006
Propylene oxide[2]	0.8			14.2	2.1			15.8	Industrial sources
Purified terephthalic acid (PTA)	0.3			2.6	0.8			2. 9	Meyers, 2005
Styrene				7.7				8. 6	JPCA, 2009a
Toluene (aromatics extraction)[8]	0.1	22.5		2.0	0.1	22.5		2.2	Schyns, 2006
Toluene diisocyanate (TDI)[5]	2.8			21.7	7.0			24.1	Schyns, 2006
Xylene (aromatics extraction)	0.1	45		2.0	0.1	45		2.2	IEA Estimates
p-Xylene	0.2		6.3	0.8	0.5		6.3	0.9	Schyns, 2006
Vinyl acetate monomer[2]	3			2.8	7.5			3.1	Industrial sources
Vinyl chloride monomer	0.4		2.7		1.0		2.7		Meyers, 2005
Urea	0.3			2.2	0.6			2.5	Schyns, 2006
Plastics									
Phenolic resins[5]				10.0				11. 1	IEA Estimates

Polycarbonate	2.2			10.3				11.5	Schyns, 2006
Polyethylene, high density (HDPE)	0.9			1.0	2.2			1.1	Schyns, 2006
Polyethylene, low density (LDPE)	3.5			-2.1	8.8			-2.4	Schyns, 2006
Polyethylene, linear low density (LLDPE)	0.4			1.6	1.1			1.8	IPTS/EC, 2007a
Polyethylene terephthalate (PET)	0.7		4.1		1.8		4.1		Boustead, 2008
Polypropylene (PP)	0.9			0.1	2.2			0.1	Schyns, 2006
Polystyrene (PS)	0.4		0.5		1.0		0.5		Hydrocarbons processing, 2003
Polyvinyl chloride (PVC)	0.6		0.5	1.2	1.6		0.5	1.4	Schyns, 2006
Urea formaldehyde (UF) & other resins & fibres[9]	0.2			2.0	0.5			2. 8	Industrial sources
Synthetic rubber & latex[9]	2.5			19.9	6.2			22.1	Schyns, 2006
Inorganic									
Ammonia from natural gas[6]	0.3	20.7	10.9	-3.9	0.7	20.7	10.9	-4.3	Schyns, 2006
Ammonia from coal[6]	3.7	20.7	17.3	-1.3	9.3	20.7	17.3	-1.4	AIChE, 2008; IFA, 2009b
Ammonia from oil[6]	0.5	20.7	16.1	-1.5	0.7	20.7	16.1	-1.7	IFA, 2009b
Carbon Black[10]	1.8	32.8			4.5	32.8			Leenderste and van Veen, 2002
Chlorine[11]	10			1.9	25			2.1	IPTS/EC, 2001
Oxygen	0.6				1.6				IEA Estimates
Soda Ash[12]				10				11.1	IPTS/EC, 2004
Titanium dioxide[13]	2.8		4.1	8.4	7.0		4.1	9.3	IPTS/EC, 2007b

[1] Final energy has been converted to primary energy assuming a steam production efficiency of 90% and a power generation efficiency of 40%.

[2] Where BPT values were not available, the BPTs were estimated assuming that they are 20% lower than current specific energy use.

[3] The value for steam use (22.2 GJ_f/t) includes both the production of ethanol from fermentable sugar (13.9 GJ_f/t) and the production of fermentable sugar from agricultural crops (8.3 GJ_f/t).

[4] This dataset has been used for the entire ethylene production except for ethylene production by steam cracking of ethane, for which the fuel use is estimated to be 5 GJ/t higher. One reason for this higher fuel use is that ethane crackers are generally designed with less heat integration and higher flue gas temperatures. Another

reason is that ethane steam crackers essentially yield only ethylene whereas naphtha steam crackers produce also other compounds (propylene, butadiene, BTX); as a consequence the average calorific value of the output is larger (by approx. 2 GJ/t) in the case of ethane and propane steam crackers compared to steam crackers operated on naphtha and gas oil and therefore the process energy is also somewhat larger (higher endothermicity).

[5] No feedstock value is given for formaldehyde, melamine, TDI and phenolic resins because this has already been accounted for in the production of the relevant raw materials (*i.e.* ammonia, methanol, propylene, benzene, toluene, and urea) (see main text for explanation).

[6] Ammonia and methanol are most commonly produced from natural gas and therefore the BPT values for this feedstock are used for all countries with the exception of India and China where also coal and oil are widely used as feedstock (see text below). The best practice final energy use for oil-based ammonia production is assumed to be 30% higher compared to natural gas-based ammonia production (AIChE, 2008; IFA, 2009b). The best practice final energy use for coal-based ammonia production is assumed to 50% higher than natural gas-based ammonia production (IFA, 2009b).

The best practice final process energy use for coal-based production of methanol is assumed to be 50% higher compared to natural gas-based methanol production (process energy use for natural gas: 10 GJ/t-methanol, for coal: 15 GJ/t-methanol; IEA, 2007).

[7] Energy data for propylene extraction in FCC process were not available and have therefore been approximated using the dataset for aromatics extraction.

[8] Half of all toluene consumption is utilized as raw material in other aromatics production, *i.e.* for xylene production via hydroproportionation and for benzene production via dealkylation. Thus, one cannot assign the full calorific value (45 GJ/t) to each of these chemicals as feedstock value as it will lead to substantial double-counting. Therefore the feedstock value of toluene is corrected by the share of its consumption which is further processed to other aromatics (by 50%).

[9] The BPT value is for urea formaldehyde (UF) resin production only, however it is used for the entire product group due to lack of representative BPT energy data for each product. This process covers the production of: acrylic fibres, nylon fibres, polyester fibres, acrylontrile-butadiene-styrene (ABS), styrene acrylonitrile (SAN) resins, Melamine-formaldehyde resin, UF resin and polyester solid state resins.

The BPT value for ‘Synthetic rubber & latex’ actually stands for ethylene propylene rubber (EPDM) production. Due to lack of data, the same BPT value is used also for the production of polybutadiene (PB) rubber, styrene-butadiene rubber (SBR) and related styrene-butadiene (SB) polymers.

[10] These values are *net* energy requirements. This means that released energy in the form of steam or power is credited (see main text for explanation). For example, tail gas in carbon black production may be used for heating of dryers process and partly for steam (and sometimes power) generation. The output of tail gas is therefore deducted from the *gross* energy requirements in order to calculate the *net* energy requirements.

[11] Energy values refer to one tonne of chlorine production, but cover the electrolysis of sodium chloride as a whole, *i.e.* including the concentration of sodium hydroxide to 50% concentration. The best practice (membrane process) technique has a current density of 0.3 – 0.4 A/cm^2. Based on industry information it is acknowledged that it is typically not possible to operate the plant full-time at the energy-efficient current density. Therefore a range of current densities has been specified for the best practice performance. The steam consumed for brine preparation and sodium hydroxide (NaOH) concentration are accounted for as well as the power requirements for rectifiers. Power required for NaOH cooling, hydrogen cooling and drying, liquefaction/evaporation of chlorine and its gas compression are excluded from the system boundaries. For the by-product hydrogen, no credits are given (approximately 3.4 GJ/t-Cl_2 based on the LHV of hydrogen by-produced).

[12] BPT values refer to synthetic production only. In North America (USA and Canada), soda ash is exclusively produced by mining which requires less energy than the synthetic routes. Therefore no savings are estimated for soda ash production in the US and Canada.

[13] The values refer to the lowest recorded energy use of the chloride process route among the two processes employed world-wide. The other process is the sulphate process which is less energy efficient than the chloride process.

The BPT values in Table 1 refer to the core of the process excluding options for heat cascading and process integration of material flows across individual plants on a site and for CHP systems. However, steam exports from production processes with exothermic reactions are accounted for and are denoted as negative values (*e.g.* steam from steam cracking and from ammonia production; see Table 1). This approach is based on the assumption that all excess heat can be used on the site. Since the data in Table 1 consider energy credits (as steam, fuel or electricity), they can be referred to as specific *net* energy requirements (expressed as lower heating value).

The system boundaries of the data used in the analysis can be described as "factory gate to factory gate". For example, for steam cracking, this definition refers to the conversion of naphtha to olefins. For an intermediate chemical such as ethylene oxide, the system boundaries include the conversion of ethylene to ethylene oxide, excluding the raw material requirements and energy use required in upstream processes. The BPT values for the most important chemicals (olefins, aromatics, ammonia and several intermediates), taken from Schyns (2006), represent European rather than worldwide best practice.[8]

Most processes of the chemical and petrochemical sector result in more than *one* product. These processes represent a particular challenge when modelling the energy use and emissions. This is especially the case for steam cracking which is by far the most important multi-product process in this sector. In this publication we use the definition of High Value Chemicals (HVC) used by Solomon Associates (who are known for their benchmark studies on steam cracking). According to this definition, HVCs include ethylene, propylene from the pyrolysis gas of steam crackers, benzene (contained amounts, excluding extracted amounts), butadiene (also contained), acetylene and hydrogen sold (as fuel) (see Table 1). Unlike the definition followed in the previous IEA publication (2008a), in the present analysis toluene and xylene are not included in the definition of HVCs in spite of being extracted for subsequent use. This raises the energy use per tonne of HVC produced, but this is balanced by lower product volumes.

The average fuel use of a BPT steam cracker is 13.1 GJ per tonne of HVC (this value is therefore reported in Table 1 for all steam cracker products according to the Solomon definition). Multiplication of this value by the production volumes of HVCs (for all steam cracker products according to the Solomon definition) results in a figure for the total BPT fuel use (in PJ) of steam crackers. The same calculation is repeated for steam, electricity and feedstock in order to calculate the total energy use of steam crackers.

The extraction of aromatics from the pyrolysis gas of steam crackers and from refinery flows is a separate activity that takes place in the chemical and petrochemical sector. These processes are estimated to use an average of 2 GJ final energy per tonne of extracted benzene, toluene and xylene. The same value has also been assumed for the separation of butylenes and propylene from fluid catalytic cracking (FCC).[9]

Feedstock consumption is accounted for by means of the calorific value of the basic chemicals following the first conversion of fossil fuels to chemicals such as benzene, ethylene and propylene (see Table 1). As a result, it is not possible to attribute energy efficiency improvements to the feedstock used for the production of organic chemicals. The basic chemicals are raw materials for the production of intermediates and their derivatives. To avoid double-counting, the calorific values of intermediates and derivatives have been excluded (see Table 1).

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[8] Synthetic rubber is an exception: the BPT data used refers to the global situation, *i.e.* not to Europe.

[9] Although FCC plants are part of refineries, propylene production via this route is accounted for under the chemical and petrochemical sector (in production statistics and in energy statistics).

Since process energy use data were not available in some cases, Table 1 does not include several important processes. This concerns the production of syngas, acetylene, EPDM rubber, hydrogen peroxide, methyl ethyl ketone (MEK), nylon 6,6, propylene glycol, sodium chlorate, sodium tripolyphosphate and unsaturated polyester.

For all countries except for China and India, BPT values for the production of ammonia and methanol from natural gas have been assumed as this is the most common feedstock and requires less energy compared to other feedstocks. In China, most ammonia is made from coal (next to some natural gas and a small amount of oil) and in India a mix of natural gas and oil is used. Methanol production is almost exclusively coal-based in China. In addition, large amounts of acetylene are made from coal. Given the recent major investments in coal-based processes in China a shift to natural gas is not foreseeable. Therefore it is more suitable to choose BPT values that represent the current feedstock choice (*i.e.*, coal and oil).

Box: Estimate of world-wide breakdown of power use and electricity savings in the chemical industry

The methodology for estimating energy efficiency improvement as presented at the beginning of the section was applied only to direct fuel use (including steam). In contrast, for electricity, an overall saving potential of up to 20% has been estimated. This estimate is primarily based on data for Western Europe and is detailed in Table 2. The table shows that the saving potential is nearly exclusively related to more efficient motors and motor systems (representing approx. 65% of total power use). Other measures are electrical efficiency improvements in the core processes and more efficient lighting. Most likely, saving potentials in developing countries are above 20% (*e.g.*, 30% for small size 15-20 horsepower units in Indian chemical industry according to Sathaye *et al.*, 2006 and large opportunities exist in China by switching to membrane based and other more efficient chlorine production processes according to Weishan, 2008). In order to arrive at a better estimate of potential power savings in the chemical industry, an international survey and a thorough analysis on power use in the chemical and petrochemical sector would be required. The potentials estimated here is a first attempt to quantify the electricity savings in the chemical and petrochemical sector.

Table 2: Breakdown of power use and potential savings in the global chemical and petrochemical sector (all in *final* energy terms), 2006

Demand category	Process electricity use (EJ/yr)	Share of total electricity use (%)	Process electricity savings (EJ/yr)	Process electricity savings compared to total final electricity use (%)[1]
Electrolysis[2]	0.5	13%	0.03	1%
Motors[3]	~2.4	~65%	0.50	14%
Lighting[4]	0.25	7%	0.05	1%
Others[5]	~0.55	~15%	0.12	3%
Total	3.7	100%	0.7	19%

Source: de Almeida *et al.*, 2000; Chemweek, 2007b; IEA, 2007.

[1] Electricity savings for each demand category are expressed relative to total final power use.

[2] Associated exclusively with the electrolysis of aqueous sodium chloride solution. The average energy use follows the system boundaries of the chlor-alkali process that is explained in Footnote 11 of Table 1 and it has been estimated based on the global shares of the three process routes by 2006 (mercury, diaphragm and membrane process) (WCC, 2007). The saving potential for electricity is based on the assumption that the entire chlorine production is shifted to the membrane process, which is the most energy efficient technology. Currently, share of the membrane process in the global chlor-alkali industry is 47% (WCC, 2007), *i.e.* a substantial switch to the membrane process has already been made. However, the membrane process requires additional steam for NaOH concentration (from 30% process output concentration to 50% product

grade) while this is not required for the mercury technology. In contrast, the diaphragm technology demands more steam than the membrane technology. We take into account the change in steam demand as a result of the switch from the mercury and diaphragm process to the membrane process.

[3] The share of power use for motors in the chemical and petrochemical sector is not clear. A share of 72% is given based on a survey that covers the industries of France, Italy and U.K. (de Almeida *et al.*, 2000). The only other reliable source available is MECS (Manufacturing Energy Consumption Survey) (US DoE, 2005) which reports a share of power consumption by motor systems of 57% in the US in 2002. We establish the share in the global chemical and petrochemical sector as the average of these values; this estimate is subject to uncertainties.
Estimated energy savings are primarily due to adoption of highly efficient motor units and by application of variable speed drives in the motor stock. Other improvement potentials and management opportunities (incl. systems optimization) have been accounted for in the areas of compressed air and fan systems (Radgen, 2001a, b).

[4] Electricity savings are based on energy saving potentials of industrial lighting which are in the range of 15-25% (Mills, 2002).

[5] The category "Others" includes heating, ventilation, air-conditioning (HVAC) and other non-process power uses (*e.g.* power use of office equipment).

2.3. Results of energy efficiency improvements and CO_2 emission reduction potentials by best practice technology

2.3.1. Energy efficiency index and reduction potentials

Table 3 shows the results of the indicator analysis (*Top-down* approach), according to which the BPT energy use for the chemical and petrochemical sector is 27.0 EJ (excl. electricity). Actual energy use in 2006 according to energy statistics was 31.5 EJ, resulting in an energy saving potential of around 4.5 EJ/yr (excl. electricity). The comparison of the country results of the indicator analysis (see Table 3) leads to the following main findings:

- Energy efficiency improvement potentials through the use of BPTs are of the order of 5 to 15% in Brazil, Canada, Japan, France, Italy, and Taiwan.
- In some other countries, such as Saudi Arabia and the United States, the potentials are found to be higher, *i.e.*, in the order of 20% or more.
- India and China are exceptions with negative improvement potentials, indicating that the current practice is more efficient than BPT; as we explain below this is partly related to the decision to base BPTs on coal and oil as feedstocks instead of natural gas.
- Negative improvement potentials are also found for Korea, Germany and Benelux which again implies that the existing processes are on average more efficient than BPT.

The comparison of the energy improvement potentials in Table 3 is based on the assumption that the system boundaries of the data collected are identical for all countries. For the world as a whole, an energy efficiency potential of more than 14% has been determined. This is less than the energy saving potential in some other industry sectors (IEA, 2009). The lower potential in the chemical and petrochemical sector can be explained by the high share of feedstock, for which no savings are possible. The bulk of the carbon that is stored in products is released in the use phase (*e.g.*, for dissipative product use) or in the waste stage (*e.g.*, waste incineration of polymers or wastewater treatment of spent surfactants).

The ten most energy consuming processes account for more than 85% of the final BPT energy use (including feedstock) of the chemical and petrochemical sector. Steam cracking accounts for 35%, ammonia production from natural gas and coal accounts for 17%, the extraction of aromatics accounts for 15%, and methanol and butylene production account for 4% each.[10]

Table 3: Energy efficiency potential of the chemical and petrochemical sector by application of Best Practice Technology (*Top-down* approach) for selected countries, 2006 (including both process energy and feedstock use)[1]

	Final process energy and feedstock use (incl. electricity)				Final process energy and feedstock use (excl. electricity)			
	Reported energy use (PJ/yr)	BPT energy use (PJ/yr)	EEI	Improvement potentials	Reported energy use (PJ/yr)	BPT energy use (PJ/yr)	EEI	Improvement potentials
USA	7 321	5 655	0.77	22.7%	6 412	4 928	0.77	23.1%
China	5 323	5 332	1.00	(-0.2)%	4 301	4 514	1.05	(-5.0%)
Japan	2 252	1 959	0.87	13.0%	2 053	1 800	0.88	12.3%
Korea	1 562	1 594	1.02	(-2.1%)	1 416	1 477	1.04	(-4.3%)
Saudi Arabia	1 369	1 058	0.77	22.7%	1 369	1 058	0.77	22.7%
Germany	1 241	1 209	0.97	2.6%	1 064	1 068	1.00	(-0.3%)
India	1 096	1 133	1.03	(-3.3%)	1 096	1 133	1.03	(-3.3%)
Benelux	1 092	1 147	1.05	(-5.1%)	1 004	1 077	1.07	(-7.3%)
Taiwan	859	738	0.85	14.1%	736	640	0.87	13.1%
Canada	843	766	0.91	9.2%	776	712	0.92	8.2%
France	714	631	0.88	11.5%	627	561	0.90	10.5%
Brazil[2]	651	576	0.88	11.6%	572	513	0.90	10.4%
Italy	457	408	0.89	10.7%	389	354	0.91	9.1%
World	35 217	29 940	0.85	15.0%	31 529	26 990	0.86	14.4%

Sources: Chemweek (2007a, b, c, d); IEA Energy Balances for OECD and non-OECD countries (2008b, c); IFA (2009); RFA (2009); SRI Consulting (2008); USGS (2007a, b); IEA Estimates

[1] The calculated BPT energy use (determined by multiplying the production volumes with the BPT values) has been divided for all countries by an estimated global coverage of 95% in order to account for the fact that some production processes have not been considered. The estimated coverage value of 95% was confirmed for a few countries (Brazil, France, Italy, Taiwan and the world; see Table 15), but it may be inaccurate for others. In order to account for these differences, a bottom-up approach is applied, which is explained in Appendix B.

[2] In the case of Brazil, the production of ethanol is not accounted for because this would lead to very high negative improvement potentials (-44%). This indicates that bio-ethanol manufacture is not part of the chemical and petrochemical sector in energy statistics, but part of the conversion sector or in the agro-industrial sector in Brazilian energy statistics.

The calculated energy efficiency potential for Japan is larger than expected. This contrasts with a new, preliminary analysis for Japan that suggests that most petrochemical sites in this country show an energy efficiency index (EEI) larger than 1, *i.e.* more efficient than best practice technology *or*

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[10] See Figure 2 in Appendix A for a pareto chart of the cumulative total final BPT energy use of all chemicals.

negative improvement potentials. Moreover, the improvement potentials calculated for USA and Saudi Arabia may be overestimated. These results indicate inconsistencies in international energy statistics and/or errors in the production data. Notwithstanding the uncertainties, industrial benchmark studies confirm that the improvement potential of the USA is high compared to other countries: for example, Keuken (2009) reports that the energy use of the total industry in North America is twice as high as Best Available Technology (BAT). On the other hand the chemical and petrochemical sector in Western Europe is 10 to 30% more efficient compared to North America (Keuken, 2009).

For Germany, China, India, Benelux and Korea, the estimated BPT energy use exceeds the total final energy use reported in energy statistics, *i.e.* the EEI is larger than 1 and hence the improvement potentials are negative. This implies that, in these countries, the existing processes are all as efficient as and partly even more efficient than BPT. However, the energy efficiency potentials are not necessarily limited to the difference between the energy use reported in energy statistics and the BPT value. This means that the *real* improvement potential can be larger than reported in Table 3 and that EEI values larger than 1 can be achieved. This is possible because (i) BPT values used represent the best practice in the *European* chemical and petrochemical sector only since *world-wide* best practice data were not available and the methodology applied (ii) does not account for heat cascading and (iii) no credits are given to energy efficiency improvements related to CHP.[11]

In addition, specific to China and India, BPT values for oil and coal-based production of ammonia and methanol were assumed, while for all other countries the exclusive production from natural gas was assumed. The negative improvement potentials calculated for China and India are partly caused by this decision (if BPTs were based on the use of natural gas the improvement potential for China would be +4.1% but it would remain negative for India, with a value of -0.4%). Normalizing the feedstock choice of China and India to natural gas as applied in the rest of the world hence does not solve the problem of negative improvement potentials, suggesting that this is not the only problem with the data. Further potential problems which are valid also for other countries are:

(i) In *production statistics*, the definition of the scope of the chemical and petrochemical sector as opposed to the refinery sector is a source of uncertainty. In Europe and the United States, the production of all pure chemicals including those produced on refinery sites, ethanol used as biofuel and anti-knocking agents are clearly included as products of the chemical and petrochemical sector. But it is unclear whether national and international *energy statistics* strictly follow this definition; energy statistics probably need to be improved on this point.
Additional uncertainties in energy statistics are associated with the refinery sector. In line with product classifications in Europe and North America, all BTX extraction and all propylene production has been assumed to occur in the chemical and petrochemical sector regardless whether the aromatics and the propylene originate from steam crackers or from refineries. However, BTX from naphtha extraction and propylene from fluid catalytic cracking production are generally produced in the refinery sector and may therefore be accounted for under refineries in energy statistics. This may lead to deviating approaches in some countries; energy statistics most likely still need to be improved on this point.

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[11] Owing to numerous chemical processes that demand low and medium level temperature steam, chemical and petrochemical industry has high heat demand that can potentially benefit from the steam supply of CHP plants (EUROHEATCOOL, 2006). However, all efficiency gains related to CHP have been assigned to power generation instead of allocating them partly to the power generation and partly to the chemical sector (in line with IEA energy accounting practice (IEA, 2009)). The potentials of CHP in chemical and petrochemical sector are discussed in Section 3.1.

(ii) In IEA *energy statistics*, reported *total non-energy use* (for industry/transformation/residential) and *feedstock use in petrochemicals* are only memo-items.[12] Their breakdown by types of fuels is somewhat uncertain because not all the information required is available from the questionnaires used by IEA. While natural gas (as used for the production of ammonia and methanol) and oil are reported under the memo-item *feedstock use in petrochemicals*, coal does not appear to be included. In other words, energy efficiency index is determined on the basis of a feedstock use value that may be under-reported. A possible solution would be to add relevant items of the *total non-energy use* that are potentially consumed by the chemical and petrochemical sector in addition to the memo-item *feedstock use in petrochemicals*. Examples may be bituminous, lignite and brown coal, as well as coke oven coke. On the other hand, it is not certain if one should include the entire item of so-called non-specific petroleum products because not all may be consumed by the chemical and petrochemical sector. If deeper insight can be gained both into the feedstock requirements and the composition of the product categories in energy statistics, then the memo-item *feedstock use in petrochemicals* could be corrected. This requires national energy statistics agencies to be engaged in a committed reporting system that ensures correct documentation of *feedstock use in petrochemicals* and *total non-energy use* of all industries.

(iii) For the production data, SRI Consulting served as a single authoritative source for most of the chemicals (see Footnote 6). However, SRI data differs from some country specific data sources.[13] This may be caused by the high complexity of the chemical and petrochemical sector: Numerous multi product processes are operated and for many chemicals more than one production process is employed. In addition, there are complex material (raw material and output) flows across the sub-sectors of the chemical and petrochemical industry. Therefore it is possible that some production volumes (among the 66 products) are double counted, but it is also very likely that parts of the production are left out. It would therefore be more reliable to use measured data of all major existing plants. But although such datasets have been collected in the context of the Emission Trading Scheme (ETS) in the European Union and in the context of some benchmarking projects, these data are generally confidential. Moreover, they are in any case only available for European countries.

(iv) There are several quality issues around the BPT data used. Equipment manufacturers tend to quote lower numbers than manufacturing companies in the chemical and petrochemical sector. Details about the process type are often not available, but can be important for the correct choice of the BPT value (*e.g.* gas phase versus suspension polymerization). Also the feedstock type affects the energy use, with data on coal-based processes (less common) generally being more uncertain than for processes based on natural gas and oil. Other process conditions (such as the current density in chlorine production) also play a role.

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[12] In the indicators analysis, estimated BPT energy use is compared to the final process energy use (fuels, heat and electricity) and the memo item *feedstock use in petrochemicals*, as reported in IEA Energy Statistics.

Process energy and feedstock use have been combined in this analysis in order to reduce the uncertainties caused by differences in system boundaries in energy statistics: Depending on system boundaries chosen in energy statistics of individual countries, reported values for feedstock energy sometimes include some amounts of process energy but this is not always the case. Adding up the two components reduces the uncertainties.

[13] SRI data was compared to (i) German national production statistics, (ii) U.S. production data published by American Chemistry Council (major differences in the categories BTX and polymers) and (iii) Japanese production data provided by Japan Petrochemical Industry Association (differences in various organic chemicals).

(v) A final source of uncertainty concerns the calculation of total final BPT energy use that is estimated by scaling up the energy use of a selection of 57 processes. This is done by using a scaling factor of 95%, which represents the coverage of final energy for the *world-wide* chemical and petrochemical (see Table 15 in Appendix B). It is, however, uncertain whether the 57 processes represent exactly 95% in each and every country. While for Brazil, France, Italy, Taiwan and the world, the *bottom-up* calculations confirm the energy coverage of 95%, for a number of countries the country specific coverage values are clearly higher or clearly lower than 95% (see Table 15). This proves that uniform application of an energy coverage value increases the uncertainty; therefore more work is necessary in this area.
In addition, country specific coverage values were tested for analyzing their sensitivity against alternative datasets different than applied in the bottom-up calculation. Separate analyses were conducted for countries with comparatively good data situation and those of which national statistics offices or other authoritative sources provide alternative datasets on production data and/or energy statistics.[14] It can be concluded that overall uncertainties cannot be simply reduced by applying country specific coverage values only. This is because when alternative datasets of production data and energy statistics were applied the coverage values ranged in the order of ±10 percentage point. This underlines the wide uncertainty range the coverage is subject to. If input data is comparable and harmonized across countries, then uncertainties can be reduced. This calls for collaboration to establish methodologies and standards which are globally applicable for the collection of physical production data and energy data from plants and also for improving the statistics accordingly.

Uncertainties that concern production statistics, energy statistics, production data, BPT data and the energy coverage limit the results of the *top-down* approach. They are an indication of actual energy saving potentials. They are not robust enough to provide a basis either for target setting or for ranking the countries with regard to their energy efficiency. The improvement potentials presented in Table 3 are not meaningful for negotiations in percentage terms. Nevertheless the approach provides energy efficiency values in the right ballpark, with an uncertainty of ±10% in most cases and possibly more in extreme cases (potentially for the USA). Further analyses supported by ambitious data collection schemes are required in order to corroborate the results and to correct them, wherever necessary.

Next steps should not be limited to correction of the results by improving data quality, but should also improve the gaps in the methodology. The developed methodology should be able to account for the energy efficiency potentials of combined heat and power plants by crediting efficiency gains (if any). In addition, the current approach needs to be improved by differentiating heat by temperature levels, allowing for country specific exergy analysis/heat cascading. Furthermore the established methodology should also integrate recovered energy from burning of undesired hydrocarbons that arise due to losses of selectivity (incomplete conversions). These improvements (especially CHP and heat cascading) are expected to resolve the issue of negative improvement potentials discussed above. Once the shortcomings on data issues and erroneous statistics are corrected and methodology is improved, it is also possible to apply the same approach over a historic time series that could potentially provide valuable information on sectoral trends in energy efficiency improvement.

Finally, the current methodology can serve as starting point for an energy efficiency index which goes beyond the core processes and broadens the system boundaries to cover all major options

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[14] Studied countries are Germany, USA, Japan, Korea and Belgium and the Netherlands (studied together).

within the life cycle. This would allow giving credits for natural and renewable feedstocks, *e.g.* raw materials for bio-based polymers and other bio-based chemicals, and for the treatment of post-consumer plastic waste (by recycling and heat recovery from plastic waste incineration). Regarding cogeneration, efficiency gains that fall into the conversion sector and hence outside of the boundaries of the chemical and petrochemical sector could be identified as potentials related to the sector. To conclude, an extended life cycle index can be introduced in order to cover these potentials.

2.3.2. CO_2 emission indicators and reduction potentials

The CO_2 emission analysis presented in this paper and the resulting CO_2 index refer only to *direct* fuel use and it therefore *excludes* emissions from sector's power use. As explained above (Section 2.1.2) the first step is to estimate the carbon stored in key polymers (see Table 4).

Table 4: Carbon storage in plastics in selected countries, 2006[1]

	Mt CO_2 equivalent/yr
China	175
USA	126
Korea	47
India	40
Japan	38
Germany	32
Benelux	30
Taiwan	30
Canada	21
Saudi Arabia	20
Brazil	18
France	17
Italy	14
World	833

[1] This table lists covers the quantity of carbon stored in all plastics and fibres accounted for in Table 1 (see also Footnote 9 in Table 1 for a breakdown of the product groups of resins/fibres and rubber).

We use the carbon storage in plastics for correcting the *potential* direct CO_2 emissions and for estimating *actual* direct CO_2 emissions. Table 5 shows the estimated actual direct CO_2 emissions for the key chemical and petrochemical manufacturing countries (see column showing the emissions in terms of Mt CO_2/yr). In 2006, the countries with highest CO_2 emissions in the chemical and petrochemical sector were the USA, China and Japan.

The CO_2 index reflects CO_2 savings that are achieved by BPT and process integration.[15] Two types of CO_2 indices are shown: one in which the same fuel mix as in 2006 was assumed (second column from the right in Table 5) and another in which natural gas was considered to be the only fuel (first column from right). One may expect that the CO_2 index estimated based on natural gas should be identical with the results for the energy efficiency index (EEI, see Table 3). This is actually the case when the results are not corrected for the CO_2 stored in plastics, fibres and urea (Table 4). Variation is introduced because the share of polymer production in the total output of the chemical industry differs per country. Moreover, all discussions on uncertainty of energy efficiency improvement potentials as a consequence of the quality of the available energy and production statistics, BPT values and other assumptions are also valid for the CO_2 indicator. Recalling the gap in the product scope for estimating the carbon storage and accounting for other uncertainties, the calculated CO_2 index is not suited for country specific emission reduction targets setting and neither for ranking the countries. However it suggests an emission reduction potential in the order of 20-35% with current fuel use and feedstock mix and 25-60% if a switch to natural gas is considered.

Table 5: Current direct CO_2 emissions and CO_2 Index (*Top-down* approach) calculated for two fuel use scenarios, 2006

	Current direct CO_2 emissions	CO_2 index	
	Mt CO_2/yr	Current fuel mix[1]	Switch to natural-gas
USA	278	0.63	0.51
China	148	(1.03)	0.47
Japan	111	0.80	0.53
Saudi Arabia	63	0.67	0.59
Korea	55	(1.02)	0.61
Germany	42	0.95	0.63
India	36	(1.00)	0.59
Benelux	33	(1.07)	0.85
Canada	28	0.80	0.65
France	27	0.79	0.52
Taiwan	26	0.65	0.19
Brazil	15	0.70	0.65
Italy	12	0.73	0.43
World	1 255	0.65	0.50

[1] This CO_2 index is calculated assuming that the current and future breakdown of fuel use and feedstock mix of the chemical and petrochemical sector of the selected countries are identical.

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[15] A rough estimation shows that approximately 3% additional energy savings over BPT energy use can be achieved by improvements in process integration.

3. Energy improvement potentials related to other measures: combined heat and power, recycling and energy recovery

Apart from the implementation of BPT in chemical processes there are further opportunities for reducing energy use and CO_2 emissions in the short to medium term. These are process integration, CHP and recycling and energy recovery. While we next discuss in more detail the energy saving potentials related to CHP, recycling and energy recovery, a deeper discussion regarding energy integration by heat cascading (including Pinch technology) and by process integration in material flows is excluded from this paper.

In the first two sections, the estimated energy saving potentials in the chemical and petrochemical sector from combined heat and power (CHP) and from recycling and energy recovery are discussed. Afterwards we show the energy improvement potentials by all measures with a breakdown for the chemical and petrochemical industries of selected countries.

3.1. Combined heat and power (CHP)

Combined heat and power (CHP), also called cogeneration, is a technology where electricity and steam or electricity and hot water are jointly produced. This increases the efficiency compared to separate electricity and heat generation. CHP has a long tradition in the chemical and petrochemical sector because of numerous processes that require a large quantity of heat and power that is easily and efficiently provided by cogeneration plants. Currently, CHP provides 10% to 25% of the sector's total power demand in most countries (see Table 17 in Appendix B). In countries with favourable policy regimes such as the Netherlands and Canada the share is as high as 70% to 90%.

Typically the power capacity of CHP plants is determined by the base-load heat demand of the site. If a larger share of the total heat demand is desired to be met by cogeneration, this would increase the overall installed CHP capacity; therefore resulting in primary energy savings that would also reduce CO_2 emissions. The assessment of savings by enhanced implementation of CHP is done by comparing the cogeneration fuel utilization efficiency with efficiencies of separate production of (grid) power and heat as reference. Therefore the crucial issue is the choice of a reference compared to which the savings are calculated. A specific cogeneration plant replaces electricity bought from the grid and fuels consumed in steam boilers on-site. While grid electricity is today generally generated in a range of plants with varying efficiencies and varying CO_2 emissions, the reference efficiency of steam production differs much less for industrial systems (it depends on the chosen fuel and on the size and age of the steam system).

The CHP unit can be compared with the *grid average* (**average approach**). A second option is to compare the CHP unit to a *new* unit that would deliver power to the grid (**marginal approach**). Usually the efficiency of existing power plants that supply grid electricity varies depending on the plant size, vintage and fuel. In many countries the average plant age is several decades and new plants are much more efficient than older ones. Typically a sub-critical coal-fired power plant achieves 30% efficiency,[16] the stock average coal-fired plant may have an efficiency of 35%, the average efficiency of all power plants may be 40% and a new stand-alone gas combined cycle may have an efficiency of 55%. Increasing the installed capacity of CHP often implies a switch to natural

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[16] All efficiency figures in this paper are given in lower heating values (LHV).

gas. Some argue that a gas grid connected power plant reference should be used, but this is by no means a given. In fact CHP may make gas economically more attractive. For example, in many countries CHP units are operated as base load, while gas-fired power plants connected to the grid are operated as middle or peak load. Therefore they compete with typical base load units that are often coal or nuclear plants. Depending on the reference chosen, the savings that are calculated will be very different. In extreme cases, the range of outcomes may vary from significant savings to no savings at all. In many cases there is no "true" reference; it is a matter of convention.

If a CHP plant is installed at an existing chemical site in a developed economy with low energy demand growth, energy savings can be calculated by comparing the CHP unit's power output to the average power grid efficiency, or compared to the oldest and least efficient plants that will be phased out when the new CHP unit is installed. For example in the United States, a country with very few new investments during the past decade, an efficiency of 30% for a sub-critical coal fired unit is common. In countries where the share of gas in power generation has been rising and where there is substantial investment in the power sector, it may be more plausible to compare a new CHP unit with a new grid connected NGCC plant (natural gas combined cycle plant). This type of reference is often used for countries such as South Korea, the Netherlands or the United Kingdom. But in other parts of the world such as China, coal or even nuclear may be the technology of choice for new units, typically with 35-40% efficiency.

As for the heat generation reference, the typical efficiency of average large-scale boiler stock is less than 90%. In contrast, new stand-alone boiler efficiencies can be higher than 90%. To some extent the fuel choice and the temperature of the heat generated affect the boiler efficiency (up to 107% efficiency for generation of low-temperature heat in a condensing gas boiler, but below 100% for typical industrial steam boilers). A summary of these two approaches discussed are shown in Table 6 and the related primary energy saving potentials for different cases of CHP plants are shown in Table 7.

Table 6: Summarized efficiency assumptions and relevant context

	Average approach		Marginal approach[1]	
Rationale	No capacity increase in grid power generation		Grid power generation is increasing (or being renewed)	
Relevant Context	Developed economies Existing chemical plants Grid power based on current energy mix (with substantial amount of coal and/or nuclear energy)		Emerging economies (or developed economies) New chemical plants Grid power based on natural gas	
Reference Efficiency for separate generation of power and heat	Boiler	Electricity	Boiler	Electricity
	≤90%	40%[2]	≥90%	52.5% - 60%

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[1] The application of the marginal approach can also be adequate in a developed economy where existing power plants are gradually replaced by highly efficient modern power plants and where it therefore needs to be decided whether investment are made in CHP or in separate generation.

[2] The average electricity efficiency is estimated based on IEA energy statistics for the world in year 2006 (IEA, 2008b). It represents the efficiency of grid electricity generated from all energy sources. It includes hydropower and wind, tide/wave/ocean and solar photovoltaics which are accounted for with 100% efficiency according to the IEA methodology. Excluding hydropower would result in an overall power generation efficiency of 36%.

The discussion above shows that it is difficult to select two single efficiency values for the reference heat and power production which can be applied globally. The appropriate assumptions depend on a range of factors (see above) and therefore the extent of the energy savings and the CO_2 emission reduction depends on the local circumstances and cannot be generalized to all countries. Based on Table 6 and Table 7 it can be concluded that (i) the average approach leads to primary energy savings of 20% compared to the current generation of grid power and (ii) that the marginal approach leads to primary energy savings between 4% and 10% compared to power generation from natural gas.

The amount of energy saved depends not only on the efficiency of grid power generation but also on the efficiencies of separate steam production in boilers and of the overall efficiency of cogeneration (total of heat and power produced divided by the primary energy input). Boiler efficiencies up to around 95% or beyond may be reasonable but the overall savings are less sensitive to changes in boiler efficiencies (around 1 percent point) compared to the default efficiency, at 90%. Efficiency improvements in cogeneration have a larger effect: if the CHP efficiency increases from 81% (this is the default assumption representing current best practice at the national level) to 85%-90%, then the primary savings increase by 7 to 8 percent points.

Table 7: Estimated primary energy savings by CHP for various reference power plants

Reference power plant	Fuel type	Reference efficiency		Primary energy savings[1]
		Boiler	Power	
Current[2]	Current mix	90%	40%	20%
State-of-the-art[3]	Natural gas	90%	52.5-60%	10-4%
State-of-the-art[4]	Coal	90%	50%	12%

[1] Primary energy savings are compared to average CHP efficiency of 81%.

[2] Current power efficiency has been estimated based on IEA Energy Statistics (see Footnote 2 of Table 6).

[3] State-of-the-art power efficiencies are based on the performance of two NGCC (natural gas combined cycle) power plants in Korea (52.5%) (Park and Kim, 2008) and efficiency of Siemens-E.ON CCGT (combined cycle gas turbine) power plant under construction in Irsching, Germany (60%) (E.ON, 2009a).

[4] Reference efficiency of state-of-the-art coal power plant with its start-up planned in 2015 in Wilhelmshaven, Germany (E.ON, 2009b).

As a rule of thumb, the savings of a switch to CHP will be higher when the temperature of the heat that is generated for useful purposes is lower. Also higher power-to-heat ratios for CHP units are generally favourable. However for a greenfield investment a careful evaluation is needed. Since the chemical and petrochemical sector mainly uses natural gas as fuel in many countries, the CHP plants will also utilize natural gas as fuel input. So in countries where oil or coal is the dominant fuel, additional emissions can be saved through fuel-switching.

According to the Euroheat and Power industrial heat demand survey (2006), the European chemical industry's low and medium temperature heat demand (100-400°C) is at least half of the total heat demand.[17] If all this heat demand would be supplied by cogeneration of heat and power, the theoretical maximum CHP capacity of the chemical and petrochemical sector would be reached. A study by Daniels and van Dril (2007) analyzes the potential of CHP until 2020 for number of

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[17] Europe in total includes 32 countries, two regions, namely EU-27, EFTA (excl. Lichtenstein) and also Croatia and Turkey.

electricity price and subsidy scenarios. We estimate based on the results of this study that half of the theoretical potential of low and medium temperature heat demand can be covered by CHP.[18] World-wide, this would allow realizing energy savings up to 2 EJ for the activity level (production) in 2006.[19] This would require that the share of CHP power in the chemical and petrochemical sector increases from currently 10% to 25% in most countries to 100% or that CHP power even exceeds the final demand.

Although CHP systems offer significant primary energy savings, market and policy barriers often prevent the realization of these benefits. Therefore the validity of these estimates may be discussed in view of severe investment barriers. Examples for these are emission limits as specified by the Clean Air Act (in US), highly unfavourable tax rates and feed-in tariffs. Additional barriers to greater implementation of CHP are utility law and regulatory provisions that discourage or prevent any company – other than a utility – from receiving a permit to build a power generation facility. At the same time, there is sufficient evidence to prove that, under the precondition of political will, the boundary conditions can be set in such a way that the desired goals are achieved. In an increasingly globalized world this requires internationally harmonized measures in order to avoid distorting competitiveness. Given the absence of a clear political will and the lack of internationally applied statistical standards the potentials identified here are theoretical.

There is a need for governments to clearly define CHP and then to align statistical data to ensure consistency. The European Commission is making a great effort by implementing directives that reference time series for heat and power generation efficiencies and the definition of system boundaries for CHP systems and that also include guidelines for harmonized and correct estimation of cogeneration efficiency and power-to-heat ratios. Such initiatives must also be established by all other governments for establishing consistent reporting of CHP performance to national statistics offices.

3.2. Recycling and energy recovery

At the end of the useful life of plastics, it is possible to save energy by application of mechanical recycling, feedstock recycling, and energy recovery. Mechanical recycling is by far the most widely

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[18] See Appendix C for detailed explanation of terms, *e.g.* theoretical potential.

Calculating the primary energy savings by CHP systems, based on IEA estimates, the power-to-heat ratio has been assumed as 1. In reality, this ratio varies by country and depends on the type of cogeneration technology used. New combined cycle gas turbines would have a power-to-heat ratio of 1, but older gas turbines or steam turbines can have ratios as low as 0.25. Therefore, by taking power-to-heat ratio of 1, it is assumed that current capacity will convert to newer CHP technologies. The yearly operation time or the load factor of industrial CHP plants was assumed to be identical with the average operation hours of chemical plants, *i.e.* 8,000 hours annually. In the chemical and petrochemical industries of some countries, the operation rates can be lower than the assumed rate, *e.g.* annually less than 80% operation rate (or 7 000 hrs) in USA (EEA, 2009).

CHP efficiency of 81% is used in the analysis based on the performance of CHP plants in operation in the Netherlands by 2006 (CBS, 2009). These CHP plants are joint ventures between energy companies and other companies which aim for the production of electricity, but they exclude power production facilities linked to waste incineration plants.

[19] Estimated primary energy savings by CHP systems are not limited by prohibiting the sales of excess power generated (when power production from CHP systems is larger than the power demand of the sector). Although, in some countries there are barriers to the sales of excess power to the grid, it is assumed that the conditions are attractive to allow power sales to the grid in all countries. Otherwise, increased implementation of CHP would be limited by sector's final power demand. In this case, the primary energy savings decrease by approximately one third.

used approach worldwide. The main alternatives to recycling are energy recovery, incineration and landfilling. In comparison to the global average, in Europe, the share of post-consumer plastics that is mechanically recycled and incinerated with energy recovery is significantly higher (see Table 8). Current statistics for 27 EU countries, Norway and Switzerland show that 20% of the post-consumer plastic waste is recycled and approximately 30% is combusted with energy recovery. The remaining 50% is disposed off either by landfilling or by incineration without energy recovery. In Japan the share of un-recovered waste is less than in Europe (40% in comparison to 50%) (Ida, 2006).

Table 8: Plastics recycling and energy recovery in selected European countries and in Europe, 2007

	Recycling (%)	Energy recovery (%)	Un-recovered waste (%)
Switzerland	23	76	1
Denmark	15	82	3
Germany	34.5	61	4.5
Sweden	27	66.5	6.5
Belgium	29	63.5	7.5
Netherlands	20.5	65.5	14
Luxemburg	18	67	15
France	16	38	46.0
Italy	20	23.5	56.5
UK	17	6.5	76.5
Ireland	18	0.0	82
Romania	10.5	4.5	85
Poland	14.5	0.5	85
EU-27 + NO/CH[1]	20.5	29	50.5

Sources: Plastics Europe 2008

[1] Represents 25% of the global plastic production (estimated at 65 Mt/yr) and an estimated plastic waste amount of 24.6 Mt/yr (2007).

Worldwide plastics consumption excluding polymers used as coatings, adhesives and other non-plastic applications is 245 Mt/yr.[20] This gives rise to an estimated plastic waste volume of 120 Mt of which around 10 Mt is recycled (this is less than 10% of the overall waste generated). If all this was recycled to produce polymer substitutes, this would represent a saving of approximately 500 PJ a year. Worldwide, about 30 Mt of plastic waste is incinerated. Today, energy recovery saves approximately 600 PJ in primary energy terms or 3% of the total process energy used in chemical and petrochemical sector.

As current best practice case, it is assumed that 25% of the total waste is recycled mechanically and the rest (75%) is incinerated with energy recovery. An average calorific value of 35 GJ/t of plastic waste and an energy recovery rate of 60% in primary terms is assumed. The savings by mechanical recycling to polymer substitutes in comparison to landfilling are estimated at 50 GJ/t. However, it is assumed that recycling leads to polymers substitutes only in one third of the cases, while two thirds

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[20] The total polymer production is reported to be 300 Mt including plastic and non-plastic applications (Plastics Europe, 2008).

are converted to non-polymer substitutes. The savings due to non-polymer substitutes were neglected because they are relatively small and very varied. No penalties are given to those countries with landfilling. Based on this set of assumptions the primary energy saving potential is estimated at 2.4 EJ per year (savings relative to landfilling). This saving potential is somewhat overestimated because it does not take account of energy savings already achieved in some countries by incineration with energy recovery. On the other hand, no credits are given to the incineration of post-consumer waste generated after the use phase following mechanical recycling (the efficiency gains by cascading are therefore not fully exploited).

Recycling and energy recovery covers the processing of post-consumer waste from products originating from the chemical and petrochemical sector. Realizing the savings potential outlined from these two options will require actions taken outside the boundary of the chemical and petrochemical sector and government support in the form of waste policies will be needed.

3.3. Results on energy efficiency improvement potentials related to other measures

While the energy saving potentials of CHP systems and recycling and energy recovery have been extensively discussed, the potentials of energy integration by heat cascading and process integration in material flows (including process intensification) are estimated based on a rough estimation as 3% additional savings over BPT energy use which is equivalent to additional final energy savings of 0.8 EJ/yr. The total worldwide potential saving from these optimization and life cycle measures and from applying BPTs (for process heat and electricity) is approximately 10.2 EJ in final energy and approximately 12.1 EJ in primary energy use (Table 10). This is equivalent to a savings of approximately 35% compared to reported final energy use in energy statistics. Regional potentials based on this methodology are shown in Figure 1.

Table 9: Worldwide energy saving potential by means of BPT and other measures related to the chemical and petrochemical sector, 2006

	Estimated savings (EJ/yr)	
	Final energy	Primary energy
BPT – Process heat[1]	4.5	5.0
BPT – Electricity[1, 2]	0.7	1.8
Process integration[1, 3]	0.8	0.9
CHP[4]	2	2
Recycling & Energy Recovery	2.2	2.4
Total	10.2	12.1

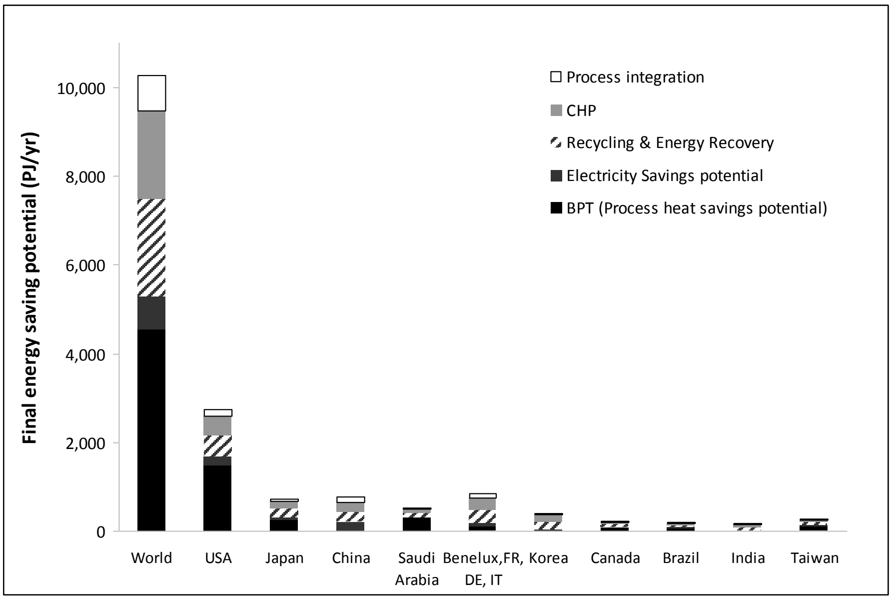
[1] Primary energy savings have been estimated assuming 40% average power generation efficiency and 90% steam production efficiency.

[2] It is likely that the total energy saving potential, which is based on the situation in OECD Europe, is under-estimated especially in developing countries and some newly industrialised countries.

[3] This is limited to heat cascading and process integration in material flows only.

[4] Energy savings from increased use of CHP are assigned to fuel due to the negligible share of power which is used as input to generate electricity.

Figure 1: Regional breakdown of final energy saving potentials by means of BPT and other measures related to the chemical and petrochemical sector, 2006[1]



[1] No BPT energy saving potential is shown for those countries with apparently negative improvement potentials.

4. Conclusions

The aim of the indicator analysis presented in this paper was to test the principle viability of the approach. It can be concluded that the analysis is workable but the quality of the input data needs to be double checked and, in most cases, improved. This especially concerns energy statistics compiled by national bodies, production data (energy statistics and companies) and BPT data. Especially for the latter a strong industry involvement is essential. If successfully managed, this will provide the basis for improving and refining the indicator approach in future, *e.g.* in order to allow separate analysis of process energy (without feedstock energy). Compared to the use of energy statistics it would be much more reliable to use measured data of all major existing plants. Such datasets have been collected in the context of the Emission Trading Scheme (ETS) in the European Union and in the context of some benchmarking projects. However, these data are generally confidential and they are anyway not available for the major countries producing (petro-) chemicals.

A striking result is that, compared to other industries, lower energy improvement potentials and emission reductions are estimated for the chemical and petrochemical sector. The main reason is that energy savings are limited to process energy while most of the sector's energy is locked into feedstock where no potentials can be specified. It can be concluded that energy efficiency measures cannot be the only solution for significant CO_2 emission reductions. To reduce emissions originating from the feedstock (in the product use/waste treatment stage), the strategies to be followed are recycling/recovery (for reprocessing the bulk of carbon sequestered in final products) and increased use of biomass feedstocks.

The discussion on CHP shows that different reference efficiencies should be used for separate heat production and power generation per country based on a range of factors, including the age of the chemical plant in question, trends in energy demand and the typical power generation technologies and fuels used locally. This makes it impossible to select values that apply globally. Consequently, energy savings by cogeneration vary widely and significant differences exist among countries. It is recommended that while CHP associated energy and GHG emission savings are assessed on global scale, various country specific circumstances should be taken into account. This also includes features that are not discussed in this paper (*e.g.* breakdown of CHP technology, efficiencies of specific CHP technologies).

Next steps should not only be limited to improvements in data quality, but should also include advancing the current methodology on saving potentials by energy integration and CHP. The indicators methodology is limited to the estimation of energy efficiency improvement potentials in the core of the processes only. A broader methodology that covers the whole life cycle will allow accounting for energy efficiency improvement potentials of other measures that are related to, but outside of the sector. These may include crediting the production of chemicals from renewable and natural feedstocks as well as including the potentials of post-consumer plastic waste treatment options.

A better understanding must be gained that allows a dedicated analysis at the country level. Benchmark activities resulting in publicly available global benchmark data for the most energy intensive chemicals are required as basis for broad cross-country analyses. A stronger collaboration is required between energy experts in companies and energy statisticians in order to improve the quality and international consistency of energy statistics. To conclude, there is an important task ahead for authorities, institutes and the chemical and petrochemical sector to catch up with the energy and CO_2 methodology development and data collection on BPT and production volume in other sectors such as iron and steel and cement.

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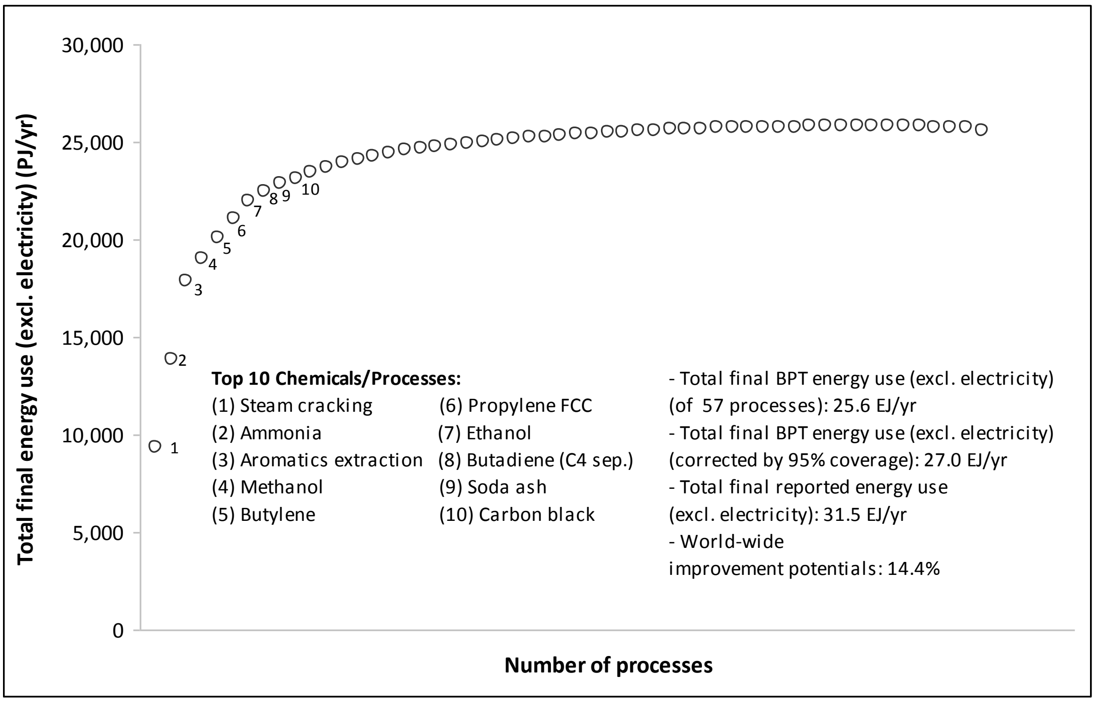
6. Appendix

A. Energy efficiency improvement potentials and CO_2 emission reduction by Best Practice Technology (BPT)

The cumulative total final BPT energy use of the global chemical and petrochemical industry is shown in Figure 2. This figure illustrates the processes that consume the largest share of energy. Around 85% of the BPT energy use of the chemical and petrochemical sector is covered by 10 processes (see text box in Figure 2). The remaining 44 processes cover another 10% of the final BPT energy use.

Figure 2: Cumulative total final BPT energy use in the global chemical and petrochemical sector in 2006 of the 57 processes included in the indicators analysis, ranked in the order of decreasing total final BPT energy use (excl. electricity but including feedstock use)[1]



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[1] The curve flattens with increasing number of processes added. The slope even becomes negative at the position of the last few data points. This is due to the negative energy use of exothermic reactions that are net steam exporters *e.g.* production of formaldehyde by oxidation of methanol. The calorific value of methanol is not taken into account because it is already covered in process number (4). Since exothermic reaction energy use is larger than the process energy inputs the net energy use is negative.

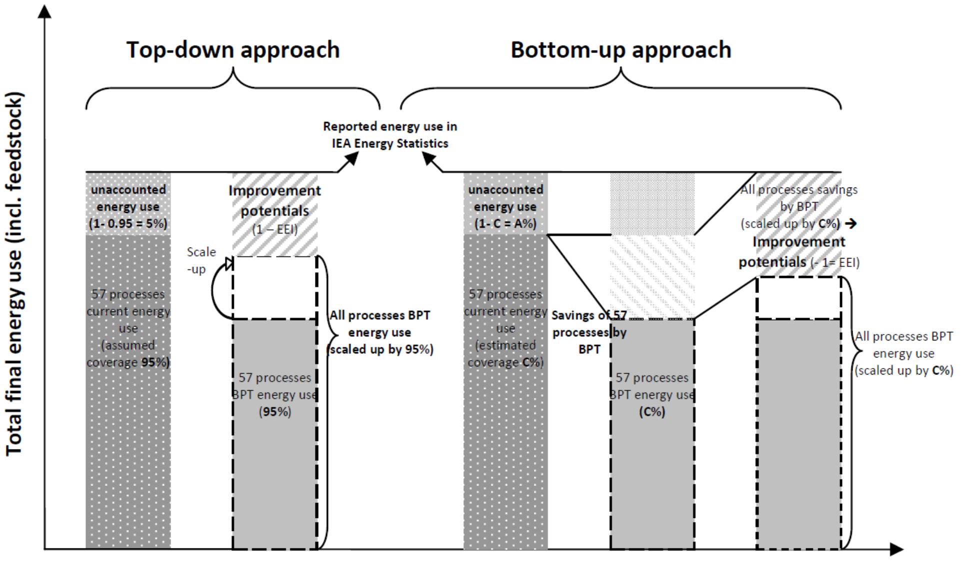
B. Indicator analysis according to the *bottom-up* approach

Bottom-up approach methodology and the results: Energy efficiency index and improvement potentials by best practice technology

Based on a number of literature sources, it was possible to collect current specific energy consumption data for the 57 processes (and 66 chemicals). This made it feasible to estimate the energy efficiency potential using a *bottom-up* approach which is presented here. The bottom-up approach can serve (i) as an alternative approach or as complementary method to the *top-down* method (see main text) and (ii) to determine the energy coverage values in order to test the assumption of 95% coverage.

The *bottom-up* approach for estimating energy efficiency potentials is applied by determining for all 57 processes the difference between the current (estimated) specific energy consumption by process and the BPT value. The multiplication of this difference with the production volume per product gives the energy savings in absolute terms. At the sector level, adding up the energy savings in absolute terms across 57 processes, scaling up the energy savings by country specific coverage values[21] and dividing this value by energy use according to IEA energy statistics give an energy efficiency improvement potential in % (Energy efficiency index = 1 – Energy efficiency improvement potential). The methodological differences for the estimation of improvement potentials by the *bottom-up* approach just discussed here and the *top-down* explained in Section 2.1.1 are shown in Figure 3.

Figure 3: Illustration of the energy efficiency improvement potentials estimation by the *top-down* and *bottom-up* approach



Note: The size of the columns is fictive and therefore energy use, improvement potentials and all other quantities are illustrative only.

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[21] Country specific coverage values are calculated by dividing the total current final energy use estimated based on 57 processes (of that country) by total final energy use reported in IEA energy statistics (of that country).

Since there are significant differences in feedstock composition and specific energy consumption among the selected countries, it is necessary to identify the situation at the country level as a basis for estimating the energy improvement potentials. The five most important processes (for the production of 9 chemicals) of the chemical and petrochemical sector – *i.e.* steam cracking (producing ethylene, a share of propylene-excluding FCC production, butadiene-contained and benzene-contained-excluding refinery production) and the production of ammonia, methanol, chlorine (incl. sodium hydroxide) and soda ash account for more than half of the sector's total final energy world-wide (including electricity). Therefore an attempt was made to differentiate the specific energy consumption values (including the effect of feedstock composition) across the studied nations in order to account for differences in energy efficiency:

(i) The estimation of the amount of energy input to the steam cracking process is essential as this is the most important process from an energy point of view. Although a number of studies provide specific energy consumption values that are region, time and raw material specific, it is still a challenging task to identify the regional energy use of steam crackers. The main reasons are the questionable data quality and the unclear definitions, making the studies hardly comparable. Solomon Associates is an authoritative source performing benchmarking surveys which cover 70% of all ethylene production capacity worldwide; however the results are mostly confidential. Sometimes non-confidential excerpts from these surveys which cover North America, Europe and Asia are cited in publicly available information. From those available, we tried to estimate the relative level of energy efficiency across the world regions. However, for a number of regions there are data gaps, especially those regions that are excluded from the public reporting of Solomon surveys. We fill these data gaps with data originating either from other sources or from personal communication with industry experts. We provide in Table 10 all data that was available to us and our estimation of the energy of steam crackers.
As a first step, we took the weighted European average specific energy use of steam crackers as a reference value for estimating all other regions (Schyns, 2006). This is equal to 15.5 GJ/t-HVC (excl. power use that amounts to approximately 0.3 GJ_e/t-HVC; in final energy terms). Although it would have been more appropriate to use the Solomon values for year 2005 (Schyns, 2008) in order for estimating the energy use of North America, we apply the values from a Solomon study with data for the year 2003 (Schyns, 2006). We do not use the former because the feedstock type these values refer to is unclear. Consequently, we estimate the energy use of the steam crackers in North America as 18.3 GJ/t-HVC based on the EEI relationship of 132 and 111 for North America and Europe respectively. The Solomon 1995 study confirms the relationship in energy use between North America and Europe.

For crackers in Asia (Japan and Korea), there are number of energy use values reported. For 1995, Ren *et al.* (2006) mention a specific energy use value of 25 GJ/t-ethylene for steam crackers that operate in Japan and Korea. When we make a comparison with the values for Japan and Korea that are reported by Weishan (2008) (see Footnote 7 in Table 10), we compute an energy efficiency improvement of 1.0% p.a in the period from 1995 until 2006, which is an acceptable rate. This confirms a specific energy use of 21-23 GJ/t-ethylene for Asia. It is necessary to convert the energy value per tonne of ethylene into a value per tonne of HVC. According to Solomon's definition, the ethylene to HVC ratio is not entirely clear, therefore we roughly apply a yield factor of 1.83 t-HVC/t-ethylene (*i.e.* 55% HVCs yield) for naphtha crackers in order to arrive at 12.6-11.5 GJ/t-HVC. We remain within the boundaries industry experts' claim, thus estimate a specific energy use value of 12.5 GJ/t-HVC for Japan and Korea; however this might be slightly on the higher side of the range. Based on the relationship of China and Japan/Korea, we estimate the energy use for China as, 16.6 GJ/t-HVC. We assume the same level of energy efficiency in China, also for India.

We estimate the world-wide energy efficiency of steam cracking based on the Solomon 1995 study. Energy efficiency in Taiwan is assumed to be similar to that of China. The differences in energy efficiency across the countries are partly caused by different feedstocks (the process energy requirements per tonne HVC are higher for gas oil and ethane than for naphtha feedstock) and by regional differences regarding the technology level.

Table 10: Energy efficiency index of selected regions according to Solomon survey and other sources

	Feedstock type	Year	US	N. America	Europe	Asia[1]	China	World
Solomon[2]	Corrected for regional mix	2003		132[2]	112	100		
Solomon[3]	Unclear	2005		112	108	100		
Solomon[4]	Corrected for regional mix	2003			145			
Solomon[6]		1995		175				
Solomon[6]	Naphtha/gas oil	1995	163					
Solomon[6]	Ethane	1995						200
Solomon[6]	Ethane/propane	1995						180
Solomon[6]	Corrected for regional mix	1995	173		151	126		164
Solomon[6]		1995	137	139	120	100		130
Industry experts[7]					~125	100		
Yanjia (2006), Weishan (2008)[8]		2004 2006				100	133	*83*
This study		2006		146	124[5]	100	132	134

Note: In the usual practice of reporting energy efficiency index of a certain process, the best practice is equated to 100. However, in this table there are number of energy efficiency index values that are equal to 100 which does not necessarily represent the best practice, but because in some studies cited or because we normalized some data on the basis of 100, they are expressed as EEI=100. In these cases the most efficient region has an energy efficiency index of 100 and all other regions are estimated accordingly. If any of the index values represent the best practice energy use, we provided this information in footnotes later on in the text.

[1] We assume that Asia represents the most energy efficient countries: Japan and Korea.

[2] Based on IEA, 2007. Although light feed steam crackers are less energy efficient than high feed ones (gas oil steam cracking being an exception), differences in the energy uses are minor.

[3] Based on Schnys, 2008. This is our own estimation of the energy values from the given benchmark graph. Type of feedstock use is not clear in the graph.

[4] Based on Schyns, 2006. The index value most likely refers to the situation of year 2003 and for EU weighted average steam crackers. In real values it refers to 15.5 GJ/t HVC of process energy (excl. power use; in final energy terms).

[5] As we normalized it to our own energy efficiency index (124), it differs from 145 (see previous footnote). However in real values it still refers to 15.5 GJ/t HVC.

[6] Based on Worrell *et al.*, 2000.

[7] As the background specific energy use values are confidential, we are able to disclose the relationship only in terms of energy efficiency index.

[8] Index values are estimated based on specific energy consumption values given in these studies. According to Yanjia (2006), in China the specific energy use of ethylene production is 29.4 GJ/t-ethylene in 2004. World best practice is 18.4 GJ/t (index value of 83). According to Weishan (2008), the specific energy use of ethylene production in China in 2006 and 2007 was 28.3 and 28 GJ/t-ethylene respectively. According to the same study, in 2006 the specific energy use values in Japan and Korea ranged between 21 and 23 GJ/t-ethylene.

(ii) For ammonia, the differences in current specific energy consumption are exceptionally large across the countries. As in the case of steam cracking, this is caused not only by different levels of technology but also by different feedstock compositions. World-wide, natural gas is by far the most important feedstock for ammonia, while gas oil is partly also consumed in India next to natural gas (see Table 11). In China, ammonia is primarily made from coal next to smaller amounts of oil and natural gas. Ammonia production from heavy oil and coal is more energy intensive compared to the use of natural gas as feedstock. Considering both the feedstock composition and the technology level, China is estimated to be 35% less efficient than Western Europe, Saudi Arabia and Taiwan. Ammonia production in Japan and Korea is estimated to be 5% more efficient than Western Europe. Compared to Western Europe, ammonia production in North America and India is estimated to be 5 and 15% less energy efficient respectively.

(iii) Methanol is primarily produced from natural gas, with China being the most important exception (nearly exclusively from coal). Due to lack of detailed information about the production structure and energy efficiency on a country basis, methanol was assumed to be produced from natural gas with identical energy efficiency for all countries except for Germany, US, India and China (estimated to be 50% less efficient).

(iv) Soda ash is produced both synthetically via the Solvay process and by extraction from natural soda ash deposits. Extraction from natural deposits is more energy efficient than synthetic production. As North America produces soda ash exclusively by extraction it is approximately 30% more efficient than the world average. Owing to lower energy efficiency in synthetic (Solvay process) soda ash production, China is around 25% less efficient than the rest of the world. In Japan and Korea, the soda ash sector includes some other synthetic processes (*e.g.* combined-soda process) which are more energy efficient than the global average of the Solvay process; therefore these two countries perform slightly better in energy terms than rest of the world.

(v) Chlorine and sodium hydroxide are co-produced via electrochemical decomposition of salt (sodium chloride). This process is a major electricity consumer while the heat demand is relatively minor (mainly consumed for concentrating NaOH to commercial level). There are three major production routes namely the membrane, mercury and diaphragm process. The membrane process is the most energy efficient one (in terms of power use), followed by the mercury and the diaphragm process. Japan is the most efficient producer because nearly the entire production is based on the membrane process. Therefore overall energy use of the chlorine electrolysis in Japan is estimated to be 10%-20% more efficient than most other countries. Although substantial energy efficiency improvements have been achieved in the Chinese industry according to experts (Weishan, 2008), energy use performance is still poor compared to rest of the world and is estimated to be around 50-60% less efficient than the industry in Western Europe.

Based on literature and personal communication with industry experts, we have estimated the breakdown of feedstock shares and process routes for different countries as given in Table 11. The specific energy consumption (SEC) assumed for the 9 production of key chemicals is given in Table 12 (all in final energy terms).

In addition to these 9 key chemicals, the current specific energy consumption of 48 processes was taken into account, leading to a total of 57 processes. For the 48 processes, specific energy consumption values are only available for Western Europe and are shown in Table 13. In other words, European average was used as proxy for the worldwide energy use for these processes. Based on available literature it was not possible to distinguish country specific energy use data for these chemicals. For some processes no data were available on the current specific energy use while the BPT values were known. In these cases, the specific energy consumption values were assumed to be 20% higher values than the BPT values.

Table 11: Estimated distribution of feedstock use and process routes for the production of nine key chemicals in selected countries, 2006

	World	Japan	Benelux	Germany	USA	Brazil	Canada	China	France	India	Italy	Korea	Saudi Arabia	Taiwan
Steam cracking														
Naphtha	47%	96%	81%	78%	33%	99%	9%	67%	82%	68%	81%	100%	21%	30%
Ethane/Propane/Butane	48%	4%	19%	9%	62%	1%	89%	N/A	16%	31%	5%	N/A	79%	70%
Gas oil	5%	N/A	N/A	13%	5%	N/A	2%	33%	2%	N/A	14%	N/A	N/A	N/A
Ammonia														
Natural gas	71%	100%	100%	67%	97%	100%	100%	22%	69%	70%	90%	N/A	100%	100%
Oil	9%	N/A	N/A	33%	3%	N/A	N/A	N/A	31%	30%	10%	100%	N/A	N/A
Coal	21%	N/A	N/A	N/A	N/A	N/A	N/A	78%	N/A	N/A	N/A	N/A	N/A	N/A
Methanol														
Natural gas	80%	N/A	100%	25%	71%	100%	100%	N/A	100%	69%	N/A	N/A	100%	100%
Oil	3%	N/A	N/A	70%	29%	N/A	N/A	N/A	N/A	31%	N/A	N/A	N/A	N/A
Coal	17%	N/A	N/A	5%	N/A	N/A	N/A	100%	N/A	N/A	N/A	N/A	N/A	N/A
Chlorine														
Diaphragma	33%	N/A	N/A	23%	70%	64%	70%	N/A	33%	N/A	N/A	N/A	33%	33%
Mercury	20%	N/A	37%	26%	12%	14%	12%	N/A	50%	7%	78%	N/A	20%	20%
Membrane	47%	100%	63%	45%	18%	22%	18%	N/A	15%	93%	22%	100%	47%	47%
Soda ash														
Solvay	59%	69%	99%	99%	N/A	100%	N/A	69%	99%	100%	99%	69%	69%	69%
Minerals	30%	4%	N/A	N/A	100%	N/A	100%	4%	N/A	N/A	N/A	4%	4%	4%
Others	11%	27%	1%	1%	N/A	N/A	N/A	27%	1%	N/A	1%	27%	27%	27%

Source: Steam cracking: Oil and Gas Journal, 2007; JPCA (2009c). Ammonia: IEA ,2007; Karagnle, 2007; Park, 2009; pers. comm. IFA, 2009; Weiss *et al.*, 2007. Methanol: IEA 2007; Methanol Institute, 2009. Chlorine: Chlistunoff, 2005; pers. comm. EuroChlor, 2009; WCC, 2007; own estimates.

Table 12. Estimated country specific energy consumption (SEC) for the production of key chemicals, 2006 (GJ$_f$/t-output)

	World	Japan	Benelux	Germany	USA	Brazil	Canada	China	France	India	Italy	Korea	Saudi Arabia	Taiwan
Steam cracking, fuel & steam[1]	16.9	12.6	15.3	15.7	18.3	17.1	18.3	16.7	15.4	16.7	15.9	12.6	18.3	16.7
Ammonia, fuel & steam[2]	41.6	35.0	35.0	37.3	38.0	36.0	37.9	49.6	37.2	40.2	35.7	42.0	36.0	37.0
Methanol, fuel & steam[3]	10.9	N/A	10.0	12.4	11.4	10.0	10.0	15.0	10.0	10.9	0.0	N/A	10.0	10.0
Chlorine , fuel & steam[4]	2.9	1.9	1.2	2.3	4.7	4.4	4.7	2.7	2.3	0.6	0.4	1.9	2.9	2.9
Chlorine, electricity[4]	10.8	10.0	11.1	11.0	10.6	10.8	10.6	14.4	11.4	11.2	12.2	10.0	10.8	10.8
Soda ash, fuel & steam[5]	10.9	10.6	11.6	11.6	6.9	11.7	6.9	13.8	11.6	13.6	12.6	10.6	11.6	13.7
Soda ash, electricity[5]	0.2	0.2	0.3	0.3	0.0	0.3	0.0	0.2	0.3	0.3	0.3	0.2	0.2	0.2

[1] The main product for steam cracking process is high value chemicals (HVC). The values account for the differences in feedstock composition across the countries as shown in Table 11. The definition of HVC follows the definition by Solomon Associates (see main text).

[2] Specific energy use value includes feedstock use. The values account for the differences in feedstock composition across the countries as shown in Table 11. Specific energy use of different feedstock is based on IEA (2007; 2009a) and for India is based on Karagnle, 2007.

[3] Specific energy use value excludes feedstock use. Except for China, an identical SEC value of 10 GJ/t-MeOH was applied globally for the natural gas based route. As depicted in Table 11, production in China is exclusively via coal based route. The specific energy use of this route is 50% higher than the natural gas route.

[4] The values account for the differences in process shares across the countries as shown in Table 11. Specific energy use of different process routes in different countries is based on Energetics, 2000; IPTS/EC 2001; Sathaye *et al.*, 2005; Weishan, 2008; Worrell *et al.*, 2000.

[5] The values account for the differences in process type across the countries as shown in Table 11. Specific energy use of different process routes is based on IPTS, 2004; IEA, 2007; Sathaye *et al.*, 2005 and Weishan, 2008. Industry's energy use in India has approximated to the energy use of China.

Table 13: Estimated *current* average specific energy consumption for the production of 57 processes (66 chemicals) in Western Europe[1]

Process	Electricity	Feedstock	Fuel	Steam	Electricity	Feedstock	Fuel	Steam	Source
	GJ$_e$/t	GJ/t	GJ$_f$/t	GJ$_f$/t	GJ$_p$/t	GJ$_p$/t	GJ$_p$/t	GJ$_p$/t	
Organic									
Acetic acid	1.0			5.7	2.5			6.3	Industrial sources
Acetone	1.3			13.9	3.3			15.5	Chauvel and Lefebvre, 1989
Acrylonitrile (ACN)	0.8		0.3	-4.5	2.1		0.3	-5.0	Schyns, 2006
Adipic acid	1.4		1.2	25.7	3.6		1.2	28.6	Chauvel and Lefebvre, 1989
Benzene (steam cracking)	See: Table 12								
Benzene (aromatics extraction)	0.1	45		3.2	0.2	45		3.6	Schyns, 2006
Butadiene (steam cracking)	See: Table 12								
Butadiene (C_4 separation)	0.7	45		7.3	1.7			8.1	Schyns, 2006
Butylene	0.7	45		7.3	0.2	45		3.6	Schyns, 2006
Caprolactam	1.7		0.2	4.1	4.2		0.2	4.5	Schyns, 2006
Cumene	0.1			1.8	0.1			2.0	Hydrocarbon processing, 2003
Cyclohexane				-1.3				-1.4	Industrial sources
Dimethyl terephthalate (DMT)			6.0				6.0		Industrial sources
Diphenylmethane diisocyanate (MDI)	4.0			1.1	10.0			1.2	Industrial sources
Ethanol	1.0	13.9		10.4	2.5	13.9		11.6	BREW Study, 2006
Ethylene	See: Table 12								
Ethylbenzene (EB)	0.1			3.9	0.2			4.4	-
Ethylene dichloride (EDC)	0.3		5.3		0.7		5.3		-
Ethylene glycol (EG)	0.3		1.1	8	0.7		1.1	9	Industrial sources
Ethylene oxide (EO)	1.2		3.1		3.1		3.1		Industrial sources
Formaldehyde	0.9			-5.7	2.3			-6.4	-
Isopropyl alcohol (IPA)	0.1		6.2	6.8	0.3		6.2	7.2	-

Maleic anhydride	0.1			2.4	0.3			2.7	-
Melamine	2.1		9.0	19.4	5.3		9.0	21.6	Schyns, 2006
Methacrylate	1.4		10.0	7.7	3.6		10.0	8.6	Chauvel and Lefebvre, 1989
Methanol from natural gas	See: Table 12								
Methanol from coal									
Methyl tert butyl ether (MTBE)	0.1			1.5	0.2			1.7	Schyns, 2006
Oxo-alcohols	1.2			2.5	3.0			2.8	-
Phenol	1.0			9.6	2.5			10.7	Chauvel and Lefebvre, 1989
Phthalic anhydride	0.8		24.0		2.1		24.0		-
Propylene (steam cracking)	See: Table 12								
Propylene (FCC)	0.1	45		3.2	0.2	45		3.6	Schyns, 2006
Propylene oxide	1.0			18.0	2.6			19.8	Industrial sources
Purified terephthalic acid (PTA)	1.7		1.6	1.7	4.2		1.6	1.8	Boustead, 2002
Styrene				9.2				10.3	-
Toluene (aromatics extraction)	0.1	45		3.2	0.2	45		3.6	Schyns, 2006
Toluene diisocyanate (TDI)	2.8		24.8	7.3	6.9		24.8	8.1	Chauvel and Lefebvre, 1989
Xylene (aromatics extraction)	0.1	45		3.2	0.2	45		3.6	Schyns, 2006
p-Xylene	0.7		1.4	6.7	1.7		1.4	7.5	IPTS/EC, 2003
Vinyl acetate monomer	3.6			4.8	9			5.3	-
Vinyl chloride monomer	0.7		3.6	0.5	1.8		3.6	0.6	IPTS/EC, 2003
Urea	0.3			3.9	0.7			4.4	Schyns, 2006
Plastics									
Phenolic resins				12.0				13.3	-
Polycarbonate	2.7			12.9	6.8			14.3	-
Polyethylene, high density (HDPE)	0.9			2.9	2.3			3.2	Schyns, 2006
Polyethylene, low density (LDPE)	3.5			0.1	8.9			0.1	Schyns, 2006
Polyethylene, linear low density	1.0			1.4	2.6			1.6	IPTS/EC, 2007b

(LLDPE)									
Polyethylene terephthalate (PET)	0.8		4.9		2.1		4.9		-
Polypropylene (PP)	1.0			1.0	2.6			1.1	Schyns, 2006
Polystyrene (PS)	0.4		0.5	0.0	0.9		0.5		Hydrocarbon processing, 2003
Polyvinyl chloride (PVC)	0.7		0.6	1.4	1.8		0.5	1.5	Schyns, 2006
Urea formaldehyde (UF) & other resins & fibres	0.2			2.5	0.5			2.8	Industrial sources
Synthetic rubber & latex	2.8			22.9	7.1			25.5	Schyns, 2006
Inorganic									
Ammonia from natural gas	See: Table 12								
Ammonia from coal									
Ammonia from oil									
Carbon Black	1.8	32.8	19.9		4.5	32.8	19.9		Leenderste and van Veen, 2002; Ulmann's, 2007
Chlorine	See: Table 12								
Oxygen	0.8				1.9				IEA, 2007
Soda Ash	See: Table 12								
Titanium dioxide[2]	5.5		13.0	11.7	13.7		13.0	13.0	IPTS/EC, 2007a

[1] For chemicals for which no source is given the current specific energy consumption has been assumed to be 20% higher than the Best Practice Technology (BPT) value given in Table 1.

[2] Specific energy consumption of titanium dioxide is estimated based on the global shares of chloride and sulphate processes and the average specific energy consumption as given in IPTS (2007a). The SEC value for TiO_2 production includes the following processes: TiO_2 usage ore preparation and oxidation/calcination, TiO_2 usage finishing and effluent treatment.

Table 14 shows the results of the indicator analysis for *bottom-up* approach, according to which the BPT energy use for the chemical and petrochemical sector is 27 EJ (excl. electricity). This results in an energy saving potential of 4.5 EJ/yr (excl. electricity). We now discuss our main findings according to the *Bottom-up* approach in more detail:

(i) Nearly all countries including the world as a whole have energy efficiency potentials in the range of 7.5-15%.
(ii) Exceptions are Japan and Korea with energy efficiency potentials of somewhat more than 5% and China and India with approximately 21% and 18% respectively.
(iii) According to the *Bottom-up* approach USA and Saudi Arabia have energy efficiency potentials of around 11% and 7.5% respectively, while they were identified as least efficient countries in the *Top-down* approach.

Table 14: Energy efficiency potential of the chemical and petrochemical sector by application of Best Practice Technology (*Bottom-up* approach) for selected countries, 2006 (including both process energy and feedstock use)[1]

	Final process energy and feedstock use (incl. Electricity)				Final process energy and feedstock use (excl. Electricity)			
	Reported energy use (PJ/yr)	BPT energy use (PJ/yr)	EEI	Improvement potentials	Reported energy use (PJ/yr)	BPT energy use (PJ/yr)	EEI	Improvement potentials
USA	7 321	6 446	0.88	11.9%	6 412	5 719	0.89	10.8%
China[2, 3]	5 323	4 220	0.79	20.7%	4 301	3 402	0.79	20.9%
Japan	2 252	2 070	0.92	8.1%	2 053	1 911	0.93	6.9%
Korea[2]	1 562	1 441	0.92	7.7%	1 416	1 325	0.94	6.5%
Saudi Arabia	1 369	1 253	0.92	8.5%	1 369	1 253	0.92	8.5%
Germany	1 241	1 075	0.87	13.4%	1 064	933	0.88	12.3%
India[2, 3]	1 096	895	0.82	18.3%	1 096	895	0.82	18.3%
Benelux[2]	1 092	973	0.89	10.8%	1 004	903	0.90	10.0%
Taiwan	859	748	0.87	13.0%	736	649	0.88	11.8%
Canada	843	709	0.84	15.9%	776	656	0.84	15.5%
France	714	634	0.89	11.3%	627	563	0.90	10.1%
Brazil[2, 4]	651	566	0.87	13.0%	572	504	0.88	12.0%
Italy	457	399	0.87	12.6%	389	345	0.89	11.3%
World	35 217	29 900	0.85	15.1%	31 529	26 949	0.85	14.5%

Sources: Chemweek (2007a, b, c, d); IEA Energy Balances for OECD and non-OECD countries (2008b, c); IFA (2009); RFA (2009); SRI Consulting (2008); USGS (2007a, b); IEA Estimates

[1] The calculated BPT energy use (based on *bottom-up* approach) has been divided by country specific coverage values (see Table 15) in order to account for the fact that some production processes have not been considered. This implies that the energy saving potentials identified for the 57 processes taken into account represent on average also the opportunities among all other processes.

[2] In the case of Brazil, the production of ethanol is not accounted for because this would lead to very high coverage of the industry (approx. 150%) indicating that energy use of bio-ethanol manufacture is excluded from the chemical and petrochemical sector energy statistics in Brazil.

According to the *Bottom-up* approach some of the results may not be considered as fully plausible, *e.g.* the finding that the energy efficiency potential of USA is smaller than Western Europe. Nevertheless the findings are closer to the expected outcome compared to the *Top-down* approach. This is, however, to a large extent an artifact which is caused by the assumed differences in current energy use across the countries (regional differentiation, see text prior to Table 11).

Total final energy use of the chemical and petrochemical sector was calculated for each country by multiplication of specific energy consumption (Table 12 and Table 13) with production volumes of each chemical. In Table 15 the resulting calculated total final energy use is compared with data from IEA energy statistics. By dividing the calculated energy use by the reported value in the IEA energy statistics the coverage is calculated (see last column in Table 15).

Table 15: Estimated energy coverage of total final energy use of 57 processes (66 chemicals) according to *bottom-up* approach (excl. electricity) for selected countries, 2006

	Reported energy use (PJ/yr)	Current Energy use (PJ/yr)	Coverage
USA	5 238	6 412	82%
Japan	1 834	2 053	89%
China	5 400	4 301	126%
Korea	1 496	1 416	106%
India	1 314	1 096	120%
Germany	1 153	1 064	108%
Benelux	1 134	1 004	113%
Saudi Arabia	1 092	1 369	80%
Canada	798	776	103%
Taiwan	683	736	93%
France	592	627	95%
Brazil	553	572	97%
Italy	378	389	97%
World[1]	29 909	31 529	95%

[1] The worldwide electricity use estimated by the *bottom-up* approach based on 57 processes amounts to 1,210 PJ/yr. Compared to reported power use in energy statistics (3,688 PJ/yr), this is equivalent to a coverage value of 33%. This indicates that relatively small quantities of power are used directly within the processes. The remaining share of power consumption is probably needed for operating motor drives and other equipment on site for which no detailed data are available.

As Table 15 shows, the 57 processes studied cover 95% of the total final energy demand of the global chemical industry. The fact that the coverage is larger than 100% for several countries points to methodological shortcomings and to problems concerning the data used. The same limitations that apply to *top-down* approach are also valid for the *bottom-up* approach. These are: i) SEC values do not account for heat cascading and therefore the total process heat requirements may be over-estimated and ii) the methodology does not consider efficiency improvements by CHP. Regarding input data, while more than 50% of the sector's energy use is covered using country specific SEC values (for 9 key chemicals), the remaining energy use has been estimated based on SEC values for

48 processes, which are applied to all countries. These SEC values refer to Western Europe and they may partly be outdated. This underpins the need to collect reliable and country specific process data for the chemical and petrochemical sector. In addition, further work is required to reduce the uncertainties related to production data and to energy statistics.

CO_2 index and reduction potentials by best practice technology

The estimated energy efficiency improvement potentials by applying the *Bottom-up* approach are presented in Table 14. By analogy direct CO_2 emissions and CO_2 index have been estimated. The same methodology explained in Section 2.1 has been repeated using these BPT (see Table 16).

Table 16: Current direct CO_2 emissions and CO_2 Index (based on BPT results from *Bottom-up* approach) calculated for two fuel use scenarios, 2006

	Current direct CO_2 emissions	CO_2 Index	
	Mt CO2/yr	Current fuel mix[1]	Switch to natural-gas
USA	278	0.81	0.67
China	148	0.50	0.07
Japan	111	0.87	0.59
Saudi Arabia	63	0.87	0.77
Korea	55	0.83	0.47
Germany	42	0.74	0.46
India	36	0.57	0.24
Benelux	33	0.76	0.57
Canada	28	0.70	0.55
France	27	0.80	0.53
Taiwan	26	0.70	0.23
Brazil	15	0.68	0.32
Italy	12	0.70	0.40
World	1,255	0.66	0.51

[1] This CO_2 index is calculated assuming that the current and future breakdown of fuel use and feedstock mix of the chemical and petrochemical sector of the selected countries are identical.

C. Combined power and heat

As explained in the main text, it is not a simple task to identify reference efficiencies for separate production of heat and power and therefore we distinguished between **average power grid efficiency** and **marginal plant efficiency**. The first generally applies when the CHP plant is installed in an existing chemical plant in a developed economy with minor changes in energy demand. The latter generally applies when the CHP system displaces a new power plant in a new chemical plant in an expanding economy.

Discussed in the main text, efficiencies of heat boilers and power generation vary between chemical plants and between countries and therefore primary energy savings achievable depend on a number of factors, such as age of the chemical plant, trend in energy demand and dominant fuel and technology in the electricity sector. For reference efficiencies, we take average efficiency values set at 40%[22] for electricity production and 90% for steam-boilers, while the average overall efficiency of CHP plants was assumed to be 81% (for electricity and heat).[23] Based on these, the maximum achievable power generation capacity by CHP for each country was calculated (see Table 17, second column from right). By comparison with statistical data on CHP (second column from left) the theoretical additional CHP potential is determined (last column). It is assumed that all capacities reported in statistics refer ultimately to the capacity in use that exclusively produces power and heat for consumption by the chemical and petrochemical sector only. In other words, there are no sales of power to the national grid, unless there is generation in excess of the industry's power demand (as reported in energy statistics) (see also Footnote 19 in main text).[24] In those cases, no restrictions were assumed for the sale of unutilized CHP power production to the grid. Therefore, the theoretical additional potential is not constrained by the power demand of the industrial plants.

Energy savings were calculated by the difference in fuel demand of the additional potential CHP capacity and the reference electricity and steam production systems. Energy savings were calculated by the difference in fuel demand of the additional potential CHP capacity and the reference electricity and steam production systems. The total primary energy savings calculated in this manner are scaled up to a world-wide estimate, thereby considering that the countries shown in Table 17 represent 77% of the global total power use. Using this approach it has been estimated that the world-wide primary energy saving potential by application of CHP amounts to up to 2 EJ today.

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[22] Efficiency is estimated based on IEA energy statistics for the world in year 2006 (IEA, 2008b). It represents the efficiency of grid electricity generated from all energy sources. It includes hydropower and wind, tide/wave/ocean and solar photovoltaics which are accounted for with 100% efficiency according to the IEA methodology. Excluding hydropower would result in an overall power generation efficiency of 36%.

[23] CHP efficiency of 81% is used in the analysis based on the performance of CHP plants in operation in the Netherlands by 2006 (CBS, 2009). These CHP plants are joint ventures between energy companies and another company which aim for the production of electricity, but they exclude power production facilities in waste incineration plants.

[24] It is, however, expedient to correct the estimated theoretical CHP capacity by a detailed accounting that allows distinguishing between the shares of heat and power sold to other sectors that originates from cogeneration plants owned by the chemical and petrochemical sector. It is unlikely that any heat sales occur, but sales of power are common even the industry itself can actually consume this portion. This requires close collaboration with national electricity and energy authorities that can allow (most likely confidential) data input on these shares.

Table 17: Installed CHP capacity in use and its estimated additional capacity potential in the chemical and petrochemical sector of selected countries[1]

	Capacity in use (GW$_e$)	Estimated Power production by CHP (PJ$_e$/yr)	Total final power use (PJ$_e$/yr)	Share of CHP power prod. over total power use (%)	Estimated maximum achievable capacity (GW$_e$)	Theoret. Addition. Potential (GW$_e$)	References
USA (2008)	25.3	729.9	908.5	80%	39.8	14.5	EEA, 2009
Japan (2008)[2]	5.7	164.2	198.5	83%	12.8	7.1	JPCA, 2009b
Germany (2006)	2.6	76.1	177.1	43%	3.6	0.9	DeStatis, 2007
NL (2006)	1.7	45.4	45.6	99%	2.6	1.0	CBS
Spain (2003(	0.6	17.3	49.8	35%	2.8	2.2	IEA, 2007
China (2005)	3.0	86.4	1022.9	8%	42.8	39.8	IEA, 2007
Italy (2003)	0.7	20.2	67.8	30%	2.5	1.8	IEA, 2007
Russia (2004)	0.7	20.2	157.3	13%	16.4	15.7	IEA, 2007
Canada (2004)	1.7	49	67.0	73%	2.1	0.4	IEA, 2007
UK (2007)	1.9	35.6	74.9	48%	2.8	0.9	BIS, 2009
Brazil (2005)	0.7	20.4	78.7	26%	3.8	3.1	EPE, 2009
India (2004)[3]	2.5	73.1	N/A	N/A	N/A	N/A	GoC, 2009

Source: IEA Energy Balances for OECD and non-OECD countries (2008b, c).

[1] The total final power use of the countries given in the Table (excl. India) account for 77% of sector's world-wide power use.

[2] For year 2008, Japan Cogeneration Center (JPCA) reported a power capacity of 1.74 GWe for CHP systems in Japanese chemical and petrochemical sector. This excludes the boiler-generator systems and the capacity installed in soda industry. According to the estimates from Japan Petrochemical Industry Association, the capacity installed in the chemical and petrochemical sector is corrected from 1.74 GWe to 5.7 GWe.

[3] As the energy statistics do not report the total final power use in the Indian chemical and petrochemical sector, it is not possible to estimate the additional CHP potential for this country.